ABSTRACT

UPPILI, BHAVANA. Electrical, Thermal and Sensory Characterization of Acidified Red Bell Peppers to Guide Microwave Process Design: A Step towards Clean Label. (Under the direction of Dr. Suzanne Johanningsmeier and Dr. Josip Simunovic).

Acidified peppers such as jalapeno, banana peppers, and red bell peppers manufactured by conventional pasteurization are widely used both in food service and households as ingredients in pizzas, sandwiches, salads, and pastas. Among these, acidified red bell peppers are known to be the most susceptible to softening during storage. Addressing consumer demands for clean label products involves finding sustainable methods for quality improvement without the use of chemical additives. This calls for exploring the feasibility of advanced processing technologies. Microwave processing has demonstrated the ability to achieve improved quality through an efficient and environmentally sustainable process as compared to conventional thermal processing. This study determined the dielectric and thermal properties that influence the heating characteristics of acidified red bell peppers when exposed to microwaves and can be used to guide the process design for the development of clean label acidified red bell peppers. The dielectric properties were modeled as a function of composition of acidified red bell peppers to understand the role of ingredients in heating behavior. As the salt content increased, the loss tangent was found to increase, while acetic acid did not play a significant role. The low loss tangent of fresh red bell peppers (~ 0.2) and transmitted power (< 50%) were identified as aspects to be addressed by equipment design to enhance heating uniformity and energy efficiency of the process. With changes in the manufacturing process, it is important to study its impact on sensory quality, which plays a key role in consumer purchase decisions. This work also established a sensory lexicon as a quality evaluation tool, that includes 46 unique attributes to characterize a wide range of fresh and preserved peppers. The lexicon includes 13 aroma, 19

flavor, 9 texture, and 4 chemical feeling factors that enable differentiation among closely related fresh and preserved pepper products. Thus, this work lays the foundation for the development of clean label acidified red bell peppers using advanced processing technologies and a sensory-guided approach.

Electrical, Thermal and Sensory Characterization of Acidified Red Bell Peppers to Guide Microwave Process Design: A Step towards Clean Label.

by
Bhavana Uppili

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Food Science

Raleigh, North Carolina
2022

APPROVED BY:

_____	_____
Suzanne Johanningsmeier Committee Co-Chair	Josip Simunovic Committee Co-Chair
_____	_____
Pablo Coronel	Deepti Salvi
_____	
Jason Osborne	

DEDICATION

I would like to dedicate this to God for supporting me through all challenges and teaching me about life at every stage of this journey.

BIOGRAPHY

Bhavana Uppili was born to her mother, Vani, and father, Uppili. She has an elder brother, Varoon, who is five years older than her. Varoon played a crucial role in her upbringing as he was her caretaker at home most of the day when her parents were out for work.

Ever since she began schooling, her parents gave her and her brother the best education within their means. While she consistently made them proud by doing well in academics, she was also an active basketball player, classical singer, and dancer. She participated in numerous sports and cultural events and won awards. On the household front, she also got trained by her parents in some of the basic finance-related tasks at the bank, and cooking, which eventually made her capable of managing independently at times of crisis. A disaster happened in her life when her father passed away suddenly when she was 13. The sorrow made her a stronger person as the years passed by, resilient to every challenge that came her way. She worked hard to graduate high school with commendable grades that got her admission into a reputed college to enter the world of food science. She was the only one who pursued science as a career in her family.

She completed her bachelors in food science and management, and pursued a masters in food technology and management immediately after. She interned at three companies while she was a student, before securing full-time employment with Thinking Forks, where she worked with immense passion for food innovation. Outside of work, she enjoyed spending time with her friends who came from different parts of the country with diverse cultural backgrounds. After a little more than three years of working, she felt the urge to explore mainstream research in academia and she landed the perfect opportunity at NC State. It was a huge change for her to tackle initially when she moved to Raleigh, especially the abnormally quiet surroundings. But

eventually her friends on Gorman Street and Schaub Hall came into her life to make numerous happy memories. She will miss the warm people and the tranquil city of Raleigh as she plans to move and take up a job with the food industry. She aspires to effect ground-breaking innovations to improve eating experiences and public health at large.

ACKNOWLEDGMENTS

I would like to immensely thank my family for putting up with my erratic routines these two and half years, and for always making time to be of emotional support. Thanks are equally due to my fiancé, Ragav, for being extremely understanding and caring.

Research during COVID was challenging in all respects, but I was fortunate to have an extremely optimistic mentor, Dr. Suzanne Johanningsmeier, who kept adapting herself to the changing times, and ensured that I was given all the resources and guidance to pursue my research. I cannot imagine coming this far without her, as she took care of me like family at some instances. She is truly a gem of an advisor that every grad student would wish for. I also want to immensely thank Dr. Josip Simunovic for giving me hope and encouragement, and teaching me to conquer the dielectrics measurement; Dr.Pablo Coronel for taking time off for me when I (or any equipment) needed guidance and reviewing my writing; Dr.Deepti Salvi for adopting me as her own student in letting me use her lab equipment; Dr. Jason Osborne for directing me on statistical analysis during committee meetings; and Dr.Dan Harris for accepting to be a substitute statistics rep at short notice and coaching me on statistical modeling. I am grateful to other faculty outside my committee as well – Dr.Haotian Zheng for letting me use his lab space during the pandemic, Dr. Keith Harris for his smiles and sharing food-grade space for my sensory panel work, Dr. Lynette Johnston for encouraging me at every instant and supporting me with lab equipment, Dr. Ilenys Péréz-Díaz for letting me use her lab equipment at a crucial time, and Dr. K.P.Sandeep for coaching me on thermal processing and being approachable for questions at all times.

It is never complete without thanking my peers at USDA and my friends – Lisa LaFountain for being a pillar of support for my research and sporadic anxiety, Dr. Matthew

Allan for mentoring me on the differential scanning calorimeter, Dr. Clinton Page for useful scientific discussions, Sandra Parker for facilitating the availability of resources, Dr.Muquarrab Qureshi, Dr.Fred Breidt and Modesta Abugu for their cheer and words of encouragement. My friends at FBNS – Manveen, Wen, Emilize, Catie, Andrew, Johnna, Riya, Carly, and Sudarshan for being there for me at all times of laughter and whining. I am also indebted to my sensory panelists for their contributions to my study and their friendship. Staff at FBNS have treated me like family and I want to thank them immensely for their support – Jb, Beth, Fred, and Mike Bumgardener. I would also like to thank all my other friends and roommates, who were my family in Raleigh – Het, Ukesh, Ramneek, Gayatri, Manraaj, Soyeb, Adithya, Lalima, Payal, Simran and Alagappan for all the breaks they made me take and their timely help for anything I asked them. Ultimately, all this work would not have happened without the Wolfline services which played a key part in my commute to the lab and safety.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: ADVANCED PROCESSING TECHNOLOGIES FOR CLEAN LABEL PICKLED VEGETABLES: OUTLOOK AND OPPORTUNITIES

1.1. ABSTRACT

Pickling of vegetables has been done from ancient times, primarily to preserve quality and prevent spoilage. More and more consumers are demanding the availability of 'clean label' foods that are free from artificial additives, contain recognizable ingredients, and are sustainably produced. The pickled vegetable industry is seeking ways to address this consumer demand for expanded markets and sustained growth. Using current production practices, chemical additives such as preservatives and calcium chloride are essential for quality retention and shelf-life extension in pickled vegetables. Even though ingredient suppliers are slowly venturing into supplying naturally derived solutions in place of chemical additives, the poor efficacy and sensory compatibility with the product along with high cost pose challenges to their use. This review details the fundamental workings of advanced processing technologies that show potential in rendering clean label pickled vegetables for the market in the immediate future. Microwave and high-pressure processing are two technologies that have been adopted at the fastest rate around the globe; about one-third of the use of such technologies have been in the processing of vegetable products. Significant advantages in using these advanced technologies, such as inactivation of microbiological and enzymatic activities, and improvements in nutritional and sensory quality of shelf stable products, along with reduced water utilization, low processing times resulting in higher throughputs, and better process efficiency, show potential in outweighing conventional pasteurization/sterilization methods in the production of 'clean label' pickled vegetables.

1.2.INTRODUCTION

Vegetable produce is perishable in nature due to low acidity (pH 5.0-6.5) and high water activity and nutrient content that provide favorable conditions for microbial spoilage. A global study on food losses revealed that approximately one third of the edible portions of food get wasted annually (FAO, 2011). Losses of vegetables occur mainly due to shortfalls in post-harvest operations (Sachdeva, Sachdev, & Sachdeva, 2013). To minimize such losses, fresh vegetable produce is processed into stable, value-added products like pickles, chutneys, dehydrates, juices, and canned and frozen products. Countries such as Malaysia, United States (US), United Kingdom, and Thailand, are among the top processors converting up to 80% of perishable produce into shelf-stable foods and beverages (Goyal, 2006).

Pickling has been an ancient practice to economically preserve the quality of vegetables, thus ensuring their availability throughout the year (Llorca et al., 2001). *Kimchi* (cabbage) in Korea, *Yan-Dong-Gua* (wax gourd) in Taiwan, spicy *achars* in India, and cucumber pickles in the Europe and Americas, are popular favorites that are being produced on industrial scale (Rolle, 2006; Swain, Anandharaj, Ray, & Rani, 2014). Pickled vegetables are commonly favored as condiments in sandwiches, soups, and appetizers. North America has been leading the pickle products market, with US being the largest consumer (360 Market Updates, 2020). In 2019, over 42% of the retail sales in the US in the condiments category came from pickles, olives, and relishes. Although a significant proportion (68%) of US consumers are engaged in the pickles market segment, only about a quarter (26%) of them associate the ‘healthy’ notion with pickles (Kamp, 2019) . With rising incidence of food- and lifestyle-related health conditions, many consumers have become more mindful of what they eat. The term ‘healthy’ is subjective and consumers look for cues on the product label to judge the healthiness of a product. Desirable

claims on the pack and familiarity with ingredients in a product prompt a ‘healthy’ perception in the minds of consumers (Asioli et al., 2017; Bazzani et al., 2019). The increasing knowledge of the importance of food in health outcomes and consumers paying greater attention to product labels has recently led to the ‘clean label’ movement. The total pickle market (including food service) is estimated to exceed $12.3 billion by 2024 (Lu, Péréz-Diáz, Hayes, & Breidt, 2020). To sustain and improve the currently projected annual growth of 3.5% (Straits Research, 2019), there is a need for the pickle industry to include offerings that satisfy consumer demands for clean label pickled vegetables.

The goal of this review is to elucidate the current practices involved in the manufacture of pickled vegetables and highlight the potential of advanced processing technologies in the development of clean label pickled vegetables.

1.3.THE ‘CLEAN LABEL’ MOVEMENT

Before the industry can respond to consumer demands, it is important to understand what ‘clean label’ exactly means. Nearly half of Americans surveyed were found to be unfamiliar with the term ‘clean label’, but the demand for ‘health’ has been a common motive in product choice (Asioli et al., 2017; Vierhile, 2016). Recent market research has revealed that 68% of US consumers are willing to pay more for food products that are free from ingredients that they consider undesirable, and switch to brands that satisfy this expectation (Cargill, 2017; Nielsen, 2017). “Real” (as found in a common household kitchen) and recognizable ingredients are what consumers look for in products, and dislike substitutes for such ingredients (Nielsen, 2017; Sweetman, 2016). The ‘clean label’ movement came about and grew with the increasing knowledge gap between consumers and manufacturers that happened as global markets and food production were burgeoning. More consumers today (about 56% of surveyed consumers who do

not trust food brands) are interested to know the ingredients and methods used for manufacturing the products they consume (Asioli et al., 2017; Nielsen, 2017) . The ingredients in a product have become the second most important factor in product purchase, after price (Nascimento, Paes, & Augusta, 2018; Sweetman, 2016).

Product claims such as 'no artificial preservatives' or 'no artificial ingredients' have been gaining the most traction (Kerry, 2019; Nascimento et al., 2018; Osborn, 2015; Scott-Thomas, 2013; Williams, 2019), appealing to 62% of the consumer population (Kalsec, 2019). Despite scientific literature showing no evidence of negative health effects of approved food additives, some consumers perceive them as unhealthy. They are also generally opposed to labelling additives using the International Numbering System (INS), perceiving it as a compromise on transparency (Chen & Hart, 2016). Claims such as 'All Natural' or '100% Natural', although desirable to consumers, need to be used on product packs carefully as oftentimes unfamiliar ingredients from natural sources, such as xanthan gum and guar gum, are not trusted by consumers (Osborn, 2015). Thus, familiarity of ingredients is of prime importance and needs to be considered when designing clean label foods.

Besides ingredients and related claims, the sustainability-related aspects of a product have also been found to influence consumers' choice (Aschemann-Witzel, Varela, & Peschel, 2019). Products that call out sustainability claims have seen quick growth. For instance, chocolates that put forth environment-friendly claims such as 'carbon neutral', 'ethically sourced', and 'made with renewable energy', grew in sales by 22% and sold five times faster than the overall category in 2017-2018 (Shoup, 2019), despite chocolates being high in sugar, an ingredient that is recognized by consumers for its role in obesity and related diseases. The proportion of consumers (50%) who prefer to buy brands that work towards redressal of ethical,

environmental and sustainability concerns, has been increasing (Kerry, 2019). Label claims such as ‘organic’, ‘locally produced’, ‘non-GMO’, ‘ethically sourced’, ‘plant-based’ or ‘vegan’, and ‘fair trade’ are perceived as sustainable methods of manufacture, and thus win consumer support (Aschemann-Witzel et al., 2019; Kerry, 2019; Williams, 2019).

Finally, a product is perceived by consumers as being healthier if it has gone through limited processing. As this information is not readily available on the product pack, consumers take cues from the length of the ingredients list and the claims displayed on the pack to infer the extent of processing a product may have undergone. For example, a brand of crackers was thought to be less processed than pasta sauce as it had a shorter ingredients list with recognizable ingredients. Also, crackers with ‘natural’ and ‘no artificial preservatives’ claims were perceived less processed than potato chips (Katz, 2011).

A classic example of the clean label trend has been demonstrated by a recent study (Aschemann-Witzel et al., 2019) with 84 consumers that showed how consumers attempt to understand the role of each ingredient in a product. Such understanding is often influenced by how the product has been portrayed – healthy, sustainable, or novel. Sugars and other sweeteners have been tagged as unhealthy, while fruit-based ingredients were perceived as natural, contributing flavor, and healthy. However, in concurrence with all other previous studies, ingredients with unfamiliar names such as pectin, xanthan gum, and beeswax were thought to be unnatural, dangerous, or weird.

In summary, the clean label trend has become a movement, signifying the shift of consumer preferences towards products that are simple, sustainable, and free from artificial ingredients (Chen & Hart, 2016; Nielsen, 2017). A clean label product is defined by consumers as one that has no additives and allergens, no chemical-sounding ingredients, has a recognizable

and short ingredients list, and is produced in a sustainable manner (Cargill, 2017; Kerry, 2019; Nielsen, 2017; Sweetman, 2016; Vierhile, 2016; Williams, 2019). So far, there is no legal definition for 'clean label' and manufacturers refrain from calling it out on the pack. Policy makers are yet to come to a common understanding of the term 'clean label' to develop a consumer-driven regulatory framework. In the meantime, private accreditation bodies have risen up to define criteria and certify products that complied with the clean label concept (Food Navigator, 2017; Mackenzie, 2017).

Consumers wish to see products that are consumed routinely and by children be available in clean label formats (Cargill, 2017). Households in the US purchase pickles every 53 days on average and more than 67% households consume pickled vegetables (Pickle Packers International, 2020). With the high consumer engagement and being a means of increasing vegetable intake to improve health (Pomerleau, Lock, Knai, & McKee, 2005), pickled vegetables present an opportunity to be considered for transforming into clean label versions.

1.3.1 Strategies towards clean label pickled vegetables

In general, the food industry has responded to the clean label demand by taking gradual efforts to supply relatively 'cleaner' products. These include the removal of synthetic ingredients like artificial sweeteners, colors, flavors, and preservatives. Several food service chains and brands have announced their plans to remove such artificial ingredients from products on their menus (Forgrieve, 2018; Galarza, 2015; George, 2016; Nestle, 2015; Neudorf, 2015; Watrous, 2015). Retailers such as Whole Foods are also advocating the clean label movement by offering only products that comply with their list of unacceptable ingredients for food (Devenyns, 2019), and are winning the trust of the growing numbers of health-driven consumers. Alternative ingredients such as natural antimicrobials are being studied for their potential to replace chemical

preservatives. Key challenges with the use of natural antimicrobials include influence on sensory properties (Brnawi et al., 2018; Gutierrez, Bourke, Lonchamp, & Barry-Ryan, 2009; Hollis et al., 2020; Valero & Giner, 2006), and in some cases lower efficacy compared to chemical preservatives. For instance, essential oils of rosemary and oregano, though efficacious antimicrobials, have intense and overpowering flavor characteristics that restrict their usage in many food matrices (Chen & Hart, 2016). Poor stability in food processing, such as with some natural coloring agents, is another limitation with their use. Additionally, the use of such natural alternatives in products requires an additional standardization step due to innate variability in biologically derived ingredients (Abbaspourrad, Padilla-Zakour, Wiedmann, Moraru, & Goddard, 2017).

Alternatively, newer processing technologies are being evaluated by researchers to avoid the use of chemical additives, overcome the limitations of conventional processes, and simultaneously yield products with desirable quality characteristics. For example, high pressure processing (HPP) and transglutaminase treatment have shown promise in developing the desired gel texture in clean label yogurts avoiding the need for chemical stabilizer systems (Loveday, Sarkar, & Singh, 2013). Similarly, ultrasound processing for 18 minutes enabled up to a 50% reduction in the phosphates required for texture development and oxidative stability of meat batters (Pinton et al., 2019). In another case, microwave processing proved to be a potential alternative to canning of ready-to-eat meals. Besides achieving the same degree of microbial inactivation (F_0 = 6 min), a 9-fold reduction in processing time, reduced water usage, and higher sensory scores could also be achieved (Tang, 2015). In the case of pickled vegetables, multiple manufacturers have removed chemical preservatives and artificial coloring agents from their products. Processing methods such as refrigeration or pasteurization have been able to partially

replace these additives but did not fully preserve the quality for the extended shelf life that is expected for pickled vegetables. Some of the newer processing technologies have shown significant advantages in quality improvement of foods and some are ready for use in commercial scale. As a step towards continuous quality improvement and catering to the growing demands for clean label, alternative processes need to be further investigated.

1.4. NEED FOR ADVANCED PROCESSING TECHNOLOGIES FOR PICKLED VEGETABLES

Despite appreciable efforts in reformulating products, these have not been successful in completely avoiding the use of chemical additives. For instance, the addition of chemical additives such as calcium chloride for texture retention (Howard & Buescher, 1990, Saldana & Meyer, 2006, Howard, Burma, & Wagner, 1994, Gu, Howard, & Wagner, 1999, Lee & Howard, 1999, Fleming, Thompson, & McFeeters, 1993) and sodium benzoate or potassium sorbate (Péréz-Diáz et al., 2013) has been necessary for shelf life extension in refrigerated fresh pack pickled vegetables and those packaged in flexible plastic packaging. Processing technologies that render the expected quality (sensory, microbiological, shelf life), and are sustainable in terms of resource (water, energy, and cost) utilization, convenience and overall value to consumers will be the ideal choice for rendering 'clean label' pickled vegetables. It is important to understand the current manufacturing practices used for pickled vegetables before proposing alternate processing technologies for this purpose.

1.4.1. Current practices in commercial pickle production

Cucumbers, cabbage, peppers, olives, and onions are among the many vegetables that are commercially processed into pickles worldwide, while carrots and beets are pickled to a lesser extent (Fleming, 1984; Ghnimi & Guizani, 2018; Péréz-Diáz et al., 2013). Pickling involves

preserving vegetables using salt and/or organic acids. While the term ‘pickles’ commonly refers to those produced from cucumbers, any vegetable preserved by fermentation or direct acidification to a pH below 4.6 is technically called a pickle or pickled vegetable (FDA, 2019; Fleming, McFeeters, & Breidt, 2001; Ghnimi & Guizani, 2018). At present, two kinds of processes are being used commercially to produce pickled vegetables. Cured-pack or fermented pickles are produced by packing vegetables in a salt brine along with dill herb, spices or extracts thereof, followed by fermenting either naturally or by a controlled process until the remaining sugars are less than 0.05% (Péréz-Diáz et al., 2013) to preserve the quality and safety of the vegetables (USDA, 2019). On the other hand, fresh pack pickles are produced by direct acidification of the vegetable without involving fermentation. In both these processes, the equilibrated pH of pickles is maintained below 4.6 throughout shelf life to control the growth of *Clostridium botulinum*. The resulting pickles may be refrigerated or pasteurized for extending shelf life. Because of using high salt levels in fermented pickles, about 1.3 billion liters of wastewater containing 79 mM of chlorides and 12,000 tons of salty sludge must be disposed of every year in the US (McMurtrie & Johanningsmeier, 2018; Péréz-Diáz et al., 2015). While considerable work has been done to address this issue (Bomben, Ourkee, Lowe, & Secor, 1974; Fleming, McFeeters, Daeschel, Humphries, & Thompson, 1988; Guillou & Floros, 1992; Johanningsmeier, Thompson, & Fleming, 2003), the fresh pack pickling process overcomes the problems associated with waste disposal as it does not involve the use of such high salt brines. Today, this process is used to produce most of the pickled vegetables in the US market. During the harvest season, approximately 60% of the produce (Personal communication, 2020) is processed into fresh pack pickles. This may equate to about 618 million pounds of cucumbers processed into fresh pack pickles in 2019 assuming all of the cucumbers available for processing

are used in pickle production (USDA, 2020). This review will focus on the manufacture of fresh pack pickles. The section below elucidates the manufacturing processes for pickled cucumbers, the general outline of which could be considered similar for other vegetables.

1.4.1.1. Acidified (fresh pack pickled) vegetables

Fresh pack pickles are commonly produced using acetic acid as the acidifying agent as it has shown the highest rate of penetration into the tissues and maximum retention of crispness in cucumbers, as compared to other acids such as lactic acid, citric acid, malic acid, and oxalic acid (Bell, Turney, & Etchells, 1972). Lactic acid may also be added to flavor the pickle with the characteristic tartness of fermented pickles (Péréz-Diáz et al., 2013). The typical manufacturing process of fresh pack cucumber pickles involves packing sized, washed, and cut cucumbers into glass jars, followed by filling with cover brine, capping, and pasteurization (Etchells & Jones, 1942; Monroe et al., 1969). Cover brine is mainly composed of acetic acid as vinegar and sodium chloride as salt. Acetic acid and optionally other organic acids at dosages of 0.5%-1.1% total acidity (USDA, 2019) are used to achieve an equilibrated pH of 3.26 to 4.05 (Bell et al., 1972; Monroe et al., 1969; Péréz-Diáz et al., 2013) and the desired tart flavor. Salt levels ranging from 0.8% to 3.66% (Péréz-Diáz et al., 2013) are incorporated for the purpose of flavoring (McFeeters & Fleming, 1997). Acidified foods with more than 3.6% of total volatile acid content coming from acetic acid, can be stable without the need for additional preservative ingredients or processes (Campbell-Platt & Anderson, 1988). The low pH and stress caused by acids can interfere with intracellular metabolic pathways, helping to restrict the growth of spoilage-causing microorganisms (Booth & Stratford, 2003). However, such a high concentration of acetic acid is accompanied by strong flavor that renders a pickle often unpalatable (Fleming et al., 1993) and low pH that degrades texture (McFeeters & Fleming,

1991). Therefore, pickled vegetables with lower acid content are refrigerated or pasteurized to preserve them for extended periods. Refrigeration involves holding pickled vegetables at 2-5℃. To ensure safety, Breidt, Hayes, & McFeeters (2007) recommended that refrigerated pickled vegetables be held for stipulated times (depending on the storage temperature) to ensure complete inactivation of pathogenic microorganisms of concern such as *Escherichia coli* O157:H7, *Salmonella enterica*, and *Listeria monocytogenes*. Additionally, Lu, Breidt, & Péréz-Diáz, (2013) reported that an increase in fumaric acid (preservative) in refrigerated pickle brine decreased the hold times required for a 5-log reduction of *E. coli* O157:H7. On the other hand, pasteurization involves heating to an internal product temperature of 74°C and holding for 15 minutes followed by prompt cooling to below 32°C (Etchells & Jones, 1942). Such a process has been found to yield a shelf-stable product that retains most of its quality characteristics for 10-12 months, provided the equilibrated acidity is at least 0.6% acetic acid and storage temperature is below 30°C (Etchells & Jones, 1942; Fleming & McFeeters, 1981; Monroe et al., 1969; Nicholas & Pflug, 1960). Pasteurization is typically carried out in a continuous tunnel pasteurizer in an industrial setting, while it could also be done in a water bath under smaller operating scales. A more energy efficient method involving three repeated hot brine refilling, has also been proposed and is capable of achieving the 5-log reduction in pathogens as required by the Food and Drug Administration (FDA) (Yavuz et al., 2018).

Similar to the fresh pack processing of cucumbers, pickled carrots have been produced by conditioning, washing, peeling, packing in a 50% w/w white vinegar solution (with acidity of 5%) in glass jars, followed by pasteurization to internal temperatures of 60°C to 93.3°C. Considering the degradation of carotenoids by heat, thermal pasteurization at 70°C for 12.45 minutes was found to be the optimum for maximum retention of carotenoids (Guerra-vargas,

Jaramillo-flores, Dorantes-alvarez, & Hernández-sánchez, 2001). Likewise, peeled and cut onions packed in 6% w/w acetic acid solution were blanched for one minute, and pasteurized for 5 mins at 85°C. This was found to be the optimum processing regime for stabilizing the desirable yellowish-green color and decreasing the loss of firmness in pickled onions (Kaack, 2017). The formulations and process conditions of selected acidified vegetables are summarized in Table 1.1. It is important to note the varying compositions and the corresponding differences in processing regimes. The limited published research on some of these acidified vegetables such as cabbage, beans, beets, carrot, onion, and cauliflower, may be due to relatively low market demand.

1.4.2. Limitations in the current practices

Pickled vegetables, though high acid products, undergo quality deterioration that is characterized by undesirable changes in texture, flavor, and color during storage (Barth, Hankinson, Zhuang, & Breidt, 2009; Fleming, Daeschel, McFeeters, & Pierson, 1989; Franco et al., 2012; Pérez-Díaz, Kelling, Hale, Breidt, & McFeeters, 2007). Fresh pack pickles that do not contain preservatives may spoil due to the growth of lactic acid bacteria, yeasts, or molds, if oxygen is present (Péréz-Diáz et al., 2013). Besides microbial spoilage, enzymes also play a role in quality deterioration, such as texture loss (Cho & Buescher, 2012). To maintain the marketability of pickle products, preservation methods to control quality deterioration need to be employed.

Refrigerated storage of pickles retards but does not inactivate enzymatic and microbial activities. As a result, chemical preservatives such as sodium benzoate and potassium sorbate are often required as an additional hurdle to spoilage (Lee, 2004). The shelf life of refrigerated pickled vegetables could also be extended when combined with mild thermal pretreatments

(Buescher, Cho, & Hamilton, 2013; LaFountain, Johanningsmeier, Breidt, Stoforos, & Price, 2022).

With outbreaks of *E.coli* and *Salmonella* reported in high acid foods like apple cider and orange juice, FDA mandated processors to include a heating or pasteurization step in the manufacture of fresh pack pickled vegetables or use preservatives in place of thermal processing. Refrigerated products, only those with pH < 3.3 are exempted from this regulation (FDA, 2004). The main goal of this type of preservation is to inhibit vegetative cells of public health significance and control the growth of other non-pathogenic microorganisms. The target for thermal processing of pickled vegetables is $F_{160°F}$ = 5.6 min when pH is 4.1-4.6 (Breidt, Kay, Osborne, Ingham, & Arritt, 2014) and 1.2 min when pH is 3.4-4.1 (Breidt, Hayes, Osborne, & McFeeters, 2005). These are minimum holding times at 160°F required to achieve safety from microorganisms of public health significance such as *E. coli O157:H7*, *Listeria monocytogenes*, and *Salmonella enterica*. However, processors typically implement a 10 to 15-min holding time to additionally inactivate quality-degrading enzymes such as pectinases (Monroe et al., 1969). Though pasteurization extends shelf life and reduces the levels of salt and vinegar required for preservation, it has been found to negatively affect the sensory properties (Fleming et al., 1993; Howard et al., 1994; Lau & Tang, 2002; Rodrigo, Rodrigo, Fiszman, & Sanchez, 1997), and destroy heat-labile nutrients (Babanovska-Milenkovska, Karakasova, Stojanova, Culeva, & Murkovic, 2018; Guerra-vargas et al., 2001; Tamer, 2012). Softening of pickles has been observed over the course of storage, which may be due to residual polygalacturonase activity that is responsible for solubilization of pectin (Cho & Buescher, 2012; Fleming et al., 1993). In the case of pickled carrots, softening was also accompanied by a decrease in L* and b* values and a simultaneous increase in a* values, indicating darkening of color due to browning and loss of β-

carotene (Wang et al., 2019) possibly due to residual peroxidase. Heat processing (98°C, 30 min) of pickled cauliflower caused a significant reduction in the total phenolic content by 7-15% (Tamer, 2012), thus also affecting the nutritional quality.

In the existing preservation methods for pickled vegetables (fermentation, refrigeration, and pasteurization), deterioration in sensory quality compels processors to use additives like chemical preservatives to extend shelf life, calcium chloride for texture retention, and coloring agents to deliver consistently colored products. As the use of additives is perceived negatively by consumers, there is a need to turn to newer processing technologies to facilitate the production of clean label pickled vegetables with desirable quality and shelf life. A new manufacturing technology that is featured as being able to produce a clean label product, is likely to be accepted easily and overcome the distrust of consumers (Abbaspourrad et al., 2017).

1.5. INNOVATIVE PROCESSING TECHNOLOGIES

Manufacturers are seeking newer processing technologies that enable them to produce quality pickled vegetables with clean label features. There has been considerable research undertaken in the area of advanced food processing technologies, some of which have been found to improve the quality of fruit and vegetable products, avoiding the need for chemical additives. For example, microwave processing of mandarin juice at 90°C for 70 s resulted in 2 log reduction in microbial load similar to conventional pasteurization (90°C, 30 s), but a superior color quality. The color change (ΔE) was as low as 0.61 ± 0.04, compared to a significantly higher color deviation of 2.69 ± 0.04 in conventionally pasteurized juice (Cheng, Jia, Gui, & Ma, 2020). This avoids the need to incorporate heat-stable synthetic colorants, when such small deviations could be negligible or corrected using natural ingredients. Similarly, an almost complete color retention has been witnessed as effects of high pressure processing on Peruvian

carrot cubes (600 MPa, 5 min) analyzed after 24 h (Tribst, Leite Júnior, de Oliveira, & Cristianini, 2016), and spinach sauce treated at 500 MPa for 5 min (Medina-Meza, Barnaba, Villani, & Barbosa-Cánovas, 2015). Atmospheric or cold plasma treatments have shown potential in avoiding the use of chemical sanitizers such as chlorine in surface decontamination of fresh produce (Kim et al., 2019; Laurita et al., 2021; Min et al., 2018). This could play a promising role in protecting public health from potential carcinogen exposure from chlorine-derived compounds (Wei, Cook, & Kirk, 1985). This technology, when used to activate water as a disinfecting agent, also provides the advantages of reduced chemical and microbial species in wastewater that is beneficial for long term environmental protection (Patange, Lu, Boehm, Cullen, & Bourke, 2019). The nutritional quality also plays an important role in products to qualify for the clean label requirements. Ultrasound processing of fruit and vegetable juices such as those of apple (Abid et al., 2013), lime (Bhat, Kamaruddin, Min-Tze, & Karim, 2011), orange (Guerrouj, Sánchez-Rubio, Taboada-Rodríguez, Cava-Roda, & Marín-Iniesta, 2016), grapefruit (Aadil, Zeng, Han, & Sun, 2013), and carrot (Jabbar et al., 2014; Zou & Jiang, 2016) increased vitamin C, phenolic compounds, and antioxidant activities analyzed after processing. This increase compared to untreated juices was attributed to the removal of oxygen and breakage of cells due to cavitation and inactivation of enzymes such as polyphenol oxidase and peroxidase. Antioxidants offer significant health benefits and regular consumption of fruits and vegetables has been shown to lower the risks of chronic diseases such as cancer, cardiovascular and immune-related diseases (Chun et al., 2005). Besides improving nutrient retention, advanced technologies have also been shown to prevent heat-induced generation of toxic compounds. For instance, furan (a class 2B carcinogen) generation was 70-90% lower in vegetable-based baby foods when sterilized by ohmic heating than by the conventional retort process. This was

possibly due to lower extent of Maillard reaction and lipid oxidation occurring in ohmic heating (Hradecky, Kludska, Belkova, Wagner, & Hajslova, 2017). This is a significant feet knowing that the highest exposure to furans has been estimated for infants (EFSA CONTAM et al., 2017).

Some of the advanced food processing technologies have also been shown to improve process efficiencies by utilizing less resources (such as water, energy, time, cost) and maximizing yield. Pulsed electric field processing of apple juice enables energy saving of 58% compared to conventional pasteurization at 71.1°C, 14 s for 5-log reduction in E.coli (Rodriguez-Gonzalez, Buckow, Koutchma, & Balasubramaniam, 2015). Similarly, vacuum impregnation could reduce the time required from days to minutes for acid equilibration in pickled vegetables (Tola & Ramaswamy, 2018). Last but not the least, advanced processing technologies enable sustainable food production by creating value from wastes and lowering the waste burden on the environment. Treatment of fruit and vegetable by-products with ultrasound has been found to facilitate extraction of dietary fiber from banana bracts (Begum & Deka, 2019) and asparagus (Iwassa, Piai, & Bolanho, 2019), which could potentially be clean label ingredients used for fiber fortification in foods. The yields of these dietary fiber concentrates were as high as 71% from banana bracts and 66% from asparagus that contained up to 83% and 67% total dietary fiber respectively, and the extraction methods did not involve the use of any hazardous solvents. Despite significant benefits, many of the abovementioned technologies cannot be used standalone as these need to be optimized to be effective in improving food quality across multiple dimensions i.e., microbial, enzymatic, nutritional, and sensory. So far, many of these advanced technologies have proven to be superior to conventional thermal processing only when used in combination with other methods. However, microwave processing and high pressure processing have been shown to provide significant advantages independently, are the most

popularly adopted at industrial scale among advanced processing technologies, and are foreseen to grow at the highest rates according to industry experts (Jermann, Koutchma, Margas, Leadley, & Ros-Polsk, 2015). The following sections will focus on these technologies including the working principles, advantages over conventional processing methods, and potential in the processing of acidified vegetables.

1.5.1. Microwave processing

Microwave processing is an advanced thermal technology for pasteurization, and sterilization of foods which uses non-ionizing radiation with frequencies between 0.3 GHz and 300 GHz in the electromagnetic spectrum (Raghavan, Orsat, & Meda, 2005). As the use of microwaves can interfere with communication aided by radio waves, specific frequencies of 915 MHz and 2450 MHz have been approved and allocated by the Federal Communication Commission for food application in the US; the former being used in industrial applications, while the latter is used in both industrial and domestic applications (Salazar-González, San Martín-González, López-Malo, & Sosa-Morales, 2012; Venkatesh & Raghavan, 2004). Microwave processing has been an active area of research for decades now, as it has demonstrated the ability to achieve faster heating rates and better retention of nutritional and sensory quality compared to conventional thermal processing. Additionally, this technology also provides the opportunity to reduce energy and water consumption and enable improved sustainability in food production. The principle, equipment, and the potential use of this technology in producing clean label products has been outlined in the following sections.

1.5.1.1. Principle

The basic principle of microwave processing is that food molecules absorb microwave energy, and the resulting molecular vibrations generate heat, that inhibits microbial and enzyme activities to preserve the quality of foods (Arjmandi et al., 2017; Koskiniemi, Truong, Simunovic, & McFeeters, 2011; Munir et al., 2019). Microwaves are a form of electromagnetic radiation that consists of an oscillating electric and magnetic field. When exposed to the electric field, dipolar molecules present in food align themselves with the direction of the field. As the electric field oscillates, dipolar molecules keep realigning themselves to the direction of the field. This results in continuous oscillation of dipolar molecules (at a frequency equal to that of the field) and friction between them generating power that gets dissipated as heat. The oscillating field also causes acceleration of ions (present within food) towards the oppositely charged side of the field. This ionic migration also plays a role in generating heat within food, especially at lower microwave frequencies (Jiang, Liu, & Wang, 2017). Since foods contain very low amounts of magnetic materials such as iron and cobalt, the effect of the magnetic field is negligible (Buffler, 1993; Teseme & Weldeselassie, 2020). As food gets directly heated by absorption of microwaves without the involvement of heat transfer surfaces (as in conventional thermal processing), the mechanism of heating is called volumetric heating (Chandrasekaran et al., 2013). Volumetric heating results in rapid heating of food, thus reducing the processing times required to achieve better quality as compared to conventional thermal processing methods. The 5-log reduction time for *Listeria monocytogenes* in Kiwifruit puree was two-fold lower when heated in a microwave oven than in a circulating water bath (Benlloch-Tinoco, Igual, Rodrigo, & Martínez-Navarrete, 2013). However, the processing time is highly dependent on the properties of the food such as size, shape (Dev, Raghavan, & Gariepy, 2008), density, and composition

(e.g. moisture and ionic concentration) to name a few (Heddleson & Doores, 1994; Koskiniemi, Truong, McFeeters, & Simunovic, 2012; McHugh, 2016; Steed et al., 2008) that influence the dielectric and thermal properties (i.e., specific heat capacity and thermal conductivity). The rate at which food gets heated by microwaves primarily depends on the dielectric properties, and secondarily on the specific heat capacity (Raghavan et al., 2005).

The dielectric properties determine the depth of penetration of microwaves into food and its ability to absorb microwave energy (Chandrasekaran, Ramanathan, & Basak, 2012). Dielectric properties include the dielectric constant, which is the ability of a material to absorb microwave energy, and loss factor, which is the ability to convert absorbed energy into heat (Chandrasekaran et al., 2012). Dielectric properties can be measured using different techniques (Venkatesh & Raghavan, 2005), but the most commonly adopted method uses an open-ended coaxial probe in conjunction with a network analyzer, as it is non-destructive and convenient to use (Teseme & Weldeselassie, 2020). While this is a static method, measurements for multiphase products such as salsa con queso or those that may undergo physical transformations, e.g., protein denaturation and/or starch gelatinization at high temperatures, more accurate measurements can be obtained when carried out under continuous flow conditions (Kumar, Coronel, Simunovic, Truong, & Sandeep, 2007). The dielectric properties are measured as complex relative permittivity which explains the proportion of energy that was transmitted and absorbed by the food sample. In other terms, complex permittivity is given by the difference between the dielectric constant (ε') and a multiple of the loss factor (ε'') (Venkatesh & Raghavan, 2005).

Specific heat capacity (c_p) is a measure of the rate at which a food is capable of showing a temperature increase; the lower the specific heat capacity, the faster the rise in temperature

(Raghavan et al., 2005). Even though oils have poor dielectric properties, their heating rates using microwaves are high due to their low specific heat capacity (Heddleson & Doores, 1994). However, rapid heating of oils has shown to degrade the quality of oils faster than heating in a conventional oven. This was indicated by higher levels of thermal and oxidation degradation products and reduction in natural antioxidants such as tocopherols (Albi, Lanzón, Guinda, León, & Pérez-Camino, 1997; Caponio, Pasqualone, & Gomes, 2003; Hassanein, El-Shami, & El-Mallah, 2003; Tan, Che Man, Jinap, & Yusoff, 2001). To mitigate such quality issues in other products with low c_p, decreasing input microwave power levels can help to decrease the heating rate (Giuliani, Bevilacqua, Corbo, & Severini, 2010; Tan et al., 2001) to an extent. Specific heat capacity is directly dependent on the composition of food, and empirical equations have been developed to predict the specific heat capacity of foods with known composition (Choi & Okos, 1986). However, it is experimentally determined mostly by differential scanning calorimetry. The specific heat capacity of water is one of the highest (4176.6 J/kg °C at 20°C). Consequently, all fruits and vegetables having high moisture contents have high specific heat capacities (Ekpunobi, Ukatu, Ngene, Onyema, & Ofora, 2014; Sereno, 2000). Thus, the microwave heating characteristics of food will depend on both its physical, chemical, electrical, and thermal properties. The microwave power and frequency, mode of the applicator, and the geometry of the microwave heating system are other factors that affect the heating rates and temperature distribution in foods processed using microwaves (Raghavan et al., 2005).

In the case of pickled vegetables, the levels of salt play a critical role in dielectric properties. Increasing salt content has been found to decrease the dielectric constant and consequently the depth of penetration of microwaves (Koskiniemi et al., 2011). This happens due to an increased binding of free water by ions that is no longer available to absorb

microwaves. However, there was no significant decrease in the dielectric constant up to 2% salt in water (Peng, 2014) and additional treatments such as blanching have helped in the diffusion of acid and salt into broccoli and sweet potato tissues, thereby overcoming the challenges with microwave penetration (Koskiniemi, Craig, Truong, McFeeters, & Simunovic, 2012). As pickle manufacturers use different formulations of products containing vegetables, acid, and salt, the dielectric properties can be highly variable. High cost of the network analyzer, probes and dielectric measurement software could limit pickle processors from considering adoption of microwave processing technology if proven effective. This calls for more research into modeling the change in dielectric properties as a function of the composition of pickled vegetables, which will help in understanding the electrical properties without the need for expensive equipment. This kind of predictive modeling for dielectric constant and loss factor has been done previously for various foods as a function of composition (Brinley, Truong, Coronel, Simunovic, & Sandeep, 2008; Sipahioglu, Barringer, Taub, & Prakash, 2003; Sun, Datta, & Lobo, 1995; Wang, Tang, Rasco, Kong, & Wang, 2008), but not yet for pickled vegetables.

1.5.1.2. Equipment

Two general types of microwave processing units have been approved by the FDA for in-pack pasteurization/sterilization (MATS) (Tang et al., 2005), and continuous flow microwave processing (Coronel et al., 2005; Drozd & Simunovic, 2017; Simunovic, 2017; Simunovic et al., 2014, 2017; Simunovic & Drozd, 2012). The difference between the two types is that the former technology involves the microwave processing of prepackaged food (Lau & Tang, 2002; Tang et al., 2005; Tang, 2015; Tang et al., 2018; Tang et al., 2008; Zhang et al., 2018), while the latter involves microwave processing of a continuous flow of product before packaging (Coronel et al., 2005; Gentry & Roberts, 2005, 2005; Koskiniemi et al., 2011; Steed et al., 2008; Stratakos et

al., 2016). Glass and polymeric packaging (Coronel et al., 2005) are suitable for MATS method, while foil or metal-based packaging cannot be used as they do not transmit microwaves (Zhang, Hongchao, Bhunia, Tang, & Sablani, 2018). This specificity with respect to the type of packaging poses a limitation, all the more when process temperatures are higher than 100°C for sterilization (Stanley & Petersen, 2017). More exploration into the morphological changes in the packaging is being carried out to develop polymers that can withstand MATS (Zhang et al., 2017). A few studies involving the use of this technology with acidified vegetables have also encountered seal failures and bulging of packs due to pressure build-up inside the packs (Koskiniemi, Truong, McFeeters, & Simunovic, 2013; Koskiniemi et al., 2011; Koskiniemi et al., 2012). Knowing that acidified vegetables are typically sold in a variety of pack sizes, such a process needs to be optimized in terms of the power level and residence times for every pack size, which is time-consuming and could limit processors from exploring new pack options. When processing larger pack sizes, there is the risk of quality degradation due to extended treatment times similar to conventional processes. Thus, for acidified vegetables, continuous flow microwave processing offers advantages of reduced processing times, uniform product quality, flexibility to use a variety of pack types and sizes, process design and optimization that is independent of the package size, and high throughputs. Therefore, this review will focus on continuous flow microwave processing which was pioneered by the scientists at North Carolina State University, Raleigh, NC.

Generally, a continuous flow microwave processing unit consists of a set of magnetrons that convert electrical supply to generate microwaves of 915 MHz or 2450 MHz frequency; a waveguide and circulator, made of reflective materials, direct and distribute microwaves onto the applicator that holds the product; applicator or cavity which is a tube transparent to microwaves,

in which the product gets exposed to microwaves (McHugh, 2016; Sabliov & Boldor, 2011). Figure 1.1 shows the schematic of the equipment setup that was used to process sweet potato purees (Coronel et al., 2005). This was the first FDA-approved continuous flow microwave process for a low-acid product, as well as the first FDA-approved process overall for microwave sterilization of such foods. Yamco (Snow Hill, NC) is the first commercial party in the US that began using a microwave sterilization process for sweet potato puree and currently produces numerous other vegetable purees such as red beets, cauliflower, butternut squash, pumpkin, and carrot (Simunovic & Sandeep, 2022). Other than the above-mentioned equipment, the setup for processing sweet potato purees also included pumps and static mixers to convey and equalize temperature distribution within the product, and thermocouples to measure temperatures after every heating and mixing stages. The choice of pumps and in-line mixers will depend on the product properties i.e., viscosity, and single- or multi-phase. The holding section ensures necessary time at the target temperature for inactivation of target organism(s). Holding is followed by flash cooling using cold water, heat exchangers, or other methods such as gas injection (Simunovic et al., 2014). There are many other patented variations of the equipment setup depending on the properties of the product to be processed (Simunovic, 2017; Simunovic et al., 2014; Simunovic & Drozd, 2012).

Applicators can be of two types – single mode and multi-mode. Single mode applicators are designed in such a way that the incident microwave energy is focused on a particular position inside the cavity where the food is placed. This is typically used for research purposes as temperature control is required, and in cases when heating a food involves a phase change, e.g., microwave drying (Chandrasekaran, Ramanathan, & Basak, 2012). In Figure 1.1, a single mode applicator made of aluminum oxide (or alumina)-sleeved polytetrafluoroethylene (Teflon) which

is transparent to microwaves was recommended for withstanding high pressure (Kumar et al., 2008). Multi-mode applicators are made of reflective materials such as metal and have larger cavities. The incident microwave radiation gets reflected multiple times by the walls of the applicator, resulting in a distribution of electric field intensities (Chandrasekaran et al., 2012; Raghavan et al., 2005) intended for uniform heating. Most commercial microwave ovens have a multi-mode applicator (Tang et al., 2018). Thus, much of the equipment design is dependent on the product characteristics and process objectives.

1.5.1.3. Potential use in the production of clean label pickled vegetables

Previous literature highlights the success of microwave processing in the production of several fruit and vegetable products. In fact, this technology has also been tested for the processing of prepackaged acidified vegetables (Koskiniemi et al., 2013, 2011; Koskiniemi et al., 2012). Table 1.2 summarizes previous work in relation to continuous flow microwave processing of fruit and vegetable products, highlighting the key processing conditions used and the effects on microbiological, enzymatic, sensorial, and nutritional qualities.

Comparison of microwave processing against conventional thermal processing can be done based on different criteria in the 'clean label' context – 1) nutritional quality, 2) sensory quality, 3) enzymatic and microbiological quality, and shelf life, 4) operational capabilities, and 5) sustainability. Previous literature has cited high retention of nutritional quality of fruit and vegetable products using both continuous flow (Table 1.2) and batch microwave processing (Akdaş & Bakkalbaşı, 2017; Tian et al., 2016; Xu et al., 2014) when compared to unprocessed controls. This happens due to breaking up of the cellular structure that releases nutrients such as vitamins and phenolics that possess antioxidant capabilities. In fact, this capability of microwave processing is being tapped upon for the extraction of bioactive compounds (Druga, Vargochik, &

Simunovic, 2018), and Ripe Revival, NC has engaged in the commercial production of gummies that contain functional bioactives extracted from food by-products using a microwave-assisted process. Most commonly, total phenolic content and antioxidant capacities increased with microwave processing of fruit and vegetable products. Antioxidants are known to protect the human body from oxidative damage that in turn plays a causative role in heart diseases, cancers, and neurodegenerative diseases (Ginter, Simko, & Panakova, 2014), and are recognized by consumers to be functional and attractive constituents in food (Kerry, 2019). Moreover, this technology has also proven useful in alleviation of allergens such as that in shrimp (Dong, Wang, & Raghavan, 2021), thus improving the access to nutritious food for people with food allergies. Sensory quality encompasses color, appearance, texture, and flavor. Color changes because of microwave processing are dependent on the processing conditions such as input power, processing time, uniformity of heating, product properties, as well as the thermal susceptibility of pigments. While very few studies have mentioned visible color changes (Marszałek, Mitek, & Skąpska, 2015; Steed et al., 2008), it is not known if the instrumentally-measured color changes are beyond the visible color tolerance, and thus needs to be verified by sensory tests. Impacts on texture of vegetable products containing particulates needs more investigation, but a comparison against conventionally pasteurized pickled asparagus (Lau & Tang, 2002) and pickled sweet potatoes (Koskiniemi et al., 2013) processed using microwaves after packaging had higher cutting force. Even microwave pasteurized tomato juice had higher cloud stability that contributes to consistency and avoiding syneresis (Fachin, Loey, VanLoeyIndrawati, Ludikhuyze, & Hendrickx, 2002), despite using similar processing conditions (85°C) to achieve a microbiological load below detection limits (Stratakos et al., 2016). This can be attributed to rapid heating rates in a microwave process in turn subjecting the product to a lower degree of

pectin de-esterification. The texture losses in pickled red bell peppers and pickled broccoli (Koskiniemi et al., 2013) could have been the result of slow cooling rates, and thus requires further optimization and process controls. More sensory studies are necessary to validate these findings using human perception. However, the rapid come-up times and heating by microwaves make this technology promising in its potential for preserving pickled vegetables with minimum impact on the sensory quality.

In terms of the microbiological quality and shelf life, continuous flow microwave processing is capable of rendering low acid products stable up to 90 d under ambient conditions (Coronel et al., 2005). Subsequent industrial experience has shown this period to be 12-18 months depending on the processed materials and storage conditions (Yamco LLC). Not only has it been effective against *Salmonella* ser. Typhimurium (4-5 log reduction) in fresh jalapeno and coriander (De La Vega-Miranda, Santiesteban-López, López-Malo, & Sosa-Morales, 2012), it has also inhibited thermophilic spores of *Bacillus subtilis* and *Geobacillus stearothermophilus* in sweet potato purees (Steed et al., 2008) conferring safety and a long shelf life at ambient storage. Additionally, this technology has also been successful in 80% to 99% inactivation of enzymes such as peroxidase, polyphenol oxidase, and pectin methylesterase (Arjmandi et al., 2017; Marszałek et al., 2015; Nikdel & MacKellar, 1993), that are known to cause color and texture deterioration during storage. Achieving such high levels of microbiological and enzyme inactivation with conventional sterilization processes entails long heating times and consequent deterioration of sensorial and nutritional quality.

From operational capabilities and sustainability points of view, microwave processing in general has reduced needs for water and energy as compared to conventional pasteurization/sterilization. This is because water-consuming boilers that generate hot water or

steam are not required, and such heating operations have been found to be the most energy-intensive in food processing operations (Nikmaram & Rosentrater, 2019; Pereira & Vicente, 2010). A simple calculation done by Cho & Chung (2020) to estimate the energy consumption in sterilization of potato cubes found that microwave processing resulted in significant 20-30% energy savings over conventional sterilization using steam or superheating steam.

1.5.1.4. Challenges and opportunities

Although volumetric heating enables faster heat transfer rates, one of the major challenges with microwave processing has been non-uniform temperature distribution (Chandrasekaran et al., 2012; Kumar et al., 2008; Salazar-González et al., 2012; Vadivambal & Jayas, 2008). This occurs due to variation in many factors that affect microwave heating, such as thickness, geometry (Raaholt, 2020), dielectric properties of food, and cavity effects. Cavity effects refers to the design of the cavity that influences the depth of penetration, and presence of mixers in the cavity that facilitate heat distribution (Vadivambal & Jayas, 2008). In most cases, it has been noted that the temperature difference occurs between the center and wall regions of the applicator tube, with the segments near the wall having a lower temperature (Coronel, Simunovic, & Sandeep, 2003; Coronel et al., 2005; Salvi, Ortego, Arauz, Sabliov, & Boldor, 2009; Steed et al., 2008). Although this can be beneficial in reducing fouling (Kumar et al., 2008), such non-uniform heating can cause inadequate microbial and enzymatic inactivation leading to a loss in quality and a threat to the safety of the product. At the same time, excessive heating at the center of the cavity can cause sensory changes and nutritional loss (Nguyen, Choi, Lee, & Jun, 2013). Solutions to mitigate non-uniform heating; such as the use of static mixers (Coronel et al., 2005), helical tubes (Zhang et al., 2021), multimode (Chandrasekaran et al., 2012) and focused applicators (Drozd & Joines, 2001). Non-uniform heating can be of higher

concern in multiphase foods (Nguyen et al., 2013) such as pickled vegetables because the liquid phase will tend to heat up faster by dielectric heating and the solid phase will tend to heat slower by convection and conduction. This occurs due to the lower thermal diffusivity of the solid phase and the differences in conductivities and dielectric properties between the two phases (Nguyen et al., 2013; Sandeep & Puri, 2001). Research groups have been working on a continuous tubular microwave processing unit for pasteurizing foods with solid particulates (Raaholt, Isaksson, & Hamberg, 2013), such as a model soup with vegetables (Raaholt, Isaksson, Hamberg, Fhager, & Hamnerius, 2016), and continuous flow combination heaters with ohmic heating (Choi, Nguyen, Lee, & Jun, 2011). A smart gasket assembly has been used to measure the cross-sectional temperature distribution in a continuous flow system (Kumar et al., 2008), and numeric modeling techniques have also been suggested to predict temperature distribution profiles of microwave-processed products (Pandit, Tang, Liu, & Mikhaylenko, 2007; Campañone, Paola, & Mascheroni, 2012; Cha-um et al., 2011; Jun & Puri, 2004, 2004; Salvi et al., 2009; Yang & Gunasekaran, 2004), to guide the design of processes and equipment. Besides the challenge of non-uniform temperature distribution, high capital (around $1000-1500 per kW + necessary equipment and accessories) and operating costs could deter the adoption of microwave processing (Simunovic, 2017; Tang et al., 2018; Wray & Ramaswamy, 2015), but recent advances in the design of smaller equipment (Simunovic, 2017) for research purposes costing just $350 per kW including all equipment and accessories could pave the way for future innovations and cost optimization in the use of microwave processing.

1.5.2. High pressure processing (HPP)

As of 2015, more than 300 HPP units were operating worldwide, 54% of which were in use in North America (Huang, Wu, Lu, Shyu, & Wang, 2017). In fact, it has been the most

widely used novel processing technology in the US (Khouryieh, 2021) after microwave processing, according to food industry experts. Some of the first high-pressure processed products in the market were jams, jellies, and sauces in Japan in 1990 (Thakur & Nelson, 1998). Ever since then, the number of products produced by HPP have increased multifold, including fruit preparations, juices, guacamole, oysters and other shellfish, soups, ready to eat (RTE) meals, salsa, pet food, baby food, and processed meat products, more so with the growing demands for clean label products. In fact, at least 20% of the use of this technology is in the manufacture of vegetable products (Huang et al., 2017). The wide adoption of this technology has been attributed to high retention of sensorial and nutritional quality along with low microbial counts and extended shelf life. This has been possible by the use of pressure at near-ambient temperatures. A deeper insight into the mechanism of operation, equipment, advantages over conventional thermal processing, and challenges is provided in the following subsections.

1.5.2.1. Principle and Equipment

HPP involves loading baskets with packaged food, which are placed in a pressure chamber (Abera, 2019). The pressure chamber is filled with a pressure-transmitting (hydraulic) fluid which is often distilled water (Kuribayashi, Ohsawa, Takanami, & Kurokouchi, 1996; Mclnerney, Seccafien, Steward, & Bird, 2007; Oliveira, Ramos, Ramos, Piccoli, & Cristianini, 2015; Park, Ha, Kim, & Ha, 2017), or occasionally solvents like propylene glycol (Kamat et al., 2018), ethanol and ethylene glycol (Noma, Shimoda, & Hayakawa, 2002) or oil emulsions in the case of older machines (Balasubramanian & Balasubramaniam, 2003). When the vessel is sealed and the pressure of the fluid is increased by a hydraulic cylinder (100-600 MPa), there occurs compression (Farr, 1990), increase in pressure and temperature (Noma et al., 2002; Oey, Lille, Loey, & Hendrickx, 2008; Ramaswamy & Shao, 2010) of the fluid. The pressure and

temperature gradient established between the fluid and the food drives the uniform transfer of pressure and heat from the fluid into the food following the Pascal principle (Balasubramanian & Balasubramaniam, 2003; Zhang et al., 2011). This isostatic distribution of pressure enables HPP to be suitable regardless of product size, volume, shape, and composition (Tola & Ramaswamy, 2018; Zhang et al., 2011). After a specified holding time at the target pressure, the chamber is depressurized, and the processed food is taken out (Munir et al., 2019). Although, HPP is often referred to as a non-thermal process or a cold pasteurization process, Rasanayagam et al. (2003) revealed temperature increases of ~3°C/100MPa in water and ~8°C/100MPa in oils. This increase in temperature happens because work is done against the intermolecular forces existing inside the product, which leads to the release of energy in the form of heat under constant pressure, also known as adiabatic heating (Knoerzer, Buckow, Sanguansri, & Versteeg, 1982; Rasanayagam et al., 2003). During decompression, the product cools almost at a linear rate (Juliano, Koutchma, Sui, Barbosa-Canovas, & Sadler, 2010). The extent of temperature increase in pressure-transmitting fluids is dependent on their thermal properties (Balasubramanian & Balasubramaniam, 2003). The choice of pressure-transmitting fluid is based on its non-corrosive interaction with the walls of the pressure chamber, compressibility, change in viscosity due to application of pressure, thermal conductivity, and specific heat capacity (Balasubramanian & Balasubramaniam, 2003). Oil and organic solvents have higher compressibilities and lower specific heat capacities as compared to distilled water (Balasubramanian & Balasubramaniam, 2003)

While the magnitude of temperature increase in the product depends on the composition and initial temperature (Rasanayagam et al., 2003), heat released due to compression also plays a role in inactivation of microorganisms and enzymes (Oliveira et al., 2015). Increase in pressure

in the chamber causes cavitation in the pressure-transmitting fluid leading to inactivation of microbial cells (Munir et al., 2019). Structural changes in the microbial cell membranes (Kalchayanand, Frethem, Dunne, Sikes, & Ray, 2002), denaturation of membrane proteins (Ritz, Freulet, Orange, & Federighi, 2000) and DNA leads to inhibition of protein synthesis and key enzymes, ultimately improving microbiological quality (Considine, Kelly, Fitzgerald, Hill, & Sleator, 2008). Inhibition of microbial activity may also be caused by temporary lowering of the pH and adiabatic heating during pressure treatment (Tholozan, Ritz, Jugiau, Federighi, & Tissier, 2000). A rapid decompression in the process has been found to have smaller D and z values and higher bactericidal effect (Noma et al., 2002). Additionally, microbial inactivation also depends on the maximum pressure, adiabatic heating during the process, and pressure-tolerance of the microorganisms (Ferreira et al., 2015). In general, treatment times can range from 2 minutes up to 30 minutes depending on the type of food and operating volumes.

HPP is most commonly operated in batch mode as it is the simplest, most efficient, and commercialized mode of operation that is also suited to process composite food structures consisting of solid and liquid phases (Munir et al., 2019) similar to pickled vegetables. Semi-continuous and continuous modes, which are still in the developmental stages, are intended for pumpable products (Rastogi, Raghavarao, Balasubramaniam, Niranjan, & Knorr, 2007).

1.5.2.2. Potential use in the production of clean label pickled vegetables

There is substantial supporting literature on the significant effects of HPP on quality improvement of fruit and vegetable products compared to conventional thermal processing. These include sensorial, nutritional, microbial quality and extended shelf life.

In order to achieve low microbial counts, fruit and vegetable products are thermally processed at high temperatures with/without long heating times. This causes significant color

changes (such as darkening) possibly due to initiation of chemical reactions such Maillard browning. HPP treatment has been shown to result in significantly higher retention of color with slightly noticeable to no visual changes in pineapple juice (Wu et al., 2021), carrot juice (Gong et al., 2015), and kiwifruit puree (Yi et al., 2016), even during storage at 4℃. As HPP does not affect covalent bonds (Balny, Mozhaev, & Lange, 1997), naturally present pigments do not get degraded by HPP (Butz, Koller, Tauscher, & Wolf, 1994; Ferrari & Matteo, 1996; Garcia, Butz, & Tauscher, 2001; Sancho et al., 1999). Effects of high pressure on carotenoid and lycopene stabilities in an orange-lemon-carrot mixed juice and tomato puree respectively were insignificant (Fernandez, Butz, Bognàr, & Tauscher, 2001; Garcia et al., 2001). In fact, many studies revealed an increase in pigments, for example, increase in carotenoids by 40% in carrot homogenate (Ancos, Gonzalez, & Cano, 2000) and 53% in orange juice (Sánchez-Moreno et al., 2005). At ambient to moderate temperature, green beans treated with HPP (500 MPa, 1 min) exhibited a more intense green color (Krebbers, Matser, Koets, & Berg, 2002). These increases in pigments occurred due to increase in cell permeability and resulting leaching from the cell. Sugars play a role in the taste of fruit of vegetable products. Retention of sucrose (Niu et al., 2022) and fructose (Wu et al., 2021) was significantly higher when passionfruit puree and pineapple juice respectively were processed using high pressure. Additionally, the texture of HPP-treated vegetables such as red radish and jicama was retained to higher extents in comparison to conventional thermal processing at 85℃. The peak puncture force was similar to untreated controls and crunchiness index was significantly higher than thermally processed samples (Nguyen et al., 2010). Descriptive sensory analysis of HPP-treated passionfruit puree revealed attribute intensities to be closer to the untreated control, while deviations were larger in the conventionally pasteurized purees (Niu et al., 2022). A couple of small-scale (n=20) sensory

acceptability tests for carrot and cucumber juices found that HPP-treated products were rater higher for overall liking compared to conventionally pasteurized samples (Gong et al., 2015; Liu, Zhang, Zhao, Wang, & Liao, 2016).

While sensory quality is a necessity for any food product, enhanced nutritional quality is an additional expectation of clean label products. Almost complete retention of total vitamin C and total phenolics has been observed in pineapple juice treated at 500 MPa for 5 min (Wu et al., 2021), asparagus juice (200 MPa for 10 min) (Chen et al., 2015), and kiwifruit puree (600 MPa, 3 min) (Yi et al., 2016), while samples processed by conventional thermal treatments suffered significant losses. More than 90% retention of ascorbic acid was noted in berry purees (Patras, Brunton, Da Pieve, & Butler, 2009) and orange juice (Polydera, Stoforos, & Taoukis, 2003; Sánchez-Moreno et al., 2005). Such compounds in food have been found to be biologically active and elicit antioxidant properties (Shahidi, 2000), which was evident in higher antioxidant activities observed in these HPP-treated products (Chen et al., 2015; Patras et al., 2009; Sánchez-Moreno et al., 2005; Wu et al., 2021). Thus, HPP helps in the retention of bioactive compounds that enhance the 'healthy' image of products. Process design is primarily targeted at inhibiting the most resistant microorganisms that are of public health concern. Conventional thermal processing has been successful for years in delivering foods that are safe for consumption and shelf stable, but at the expense of compromising sensorial and nutritional quality. Despite operating at near-ambient temperatures, HPP treatment of cloudy pomegranate juice at 400 MPa for 5 min has been successful in achieving a 90-day shelf life at 4°C, which was comparable to conventionally pasteurized juice. The total aerobic count in both juices did not exceed 1 log and the yeast & mold count in HPP-treated juice was 3x lower at the end of 90 days (Chen et al., 2013). Similarly, the total mesophiles and yeast & mold counts in high pressure processed

strawberry juice (300 MPa, 1 min) did not exceed 2 log CFU/ml after 42 days at 4℃, which was comparable to juice that was conventionally pasteurized at 72℃ for 15 s (Yildiz, Pokhrel, Unluturk, & Barbosa-Cánovas, 2021). The difference in shelf lives between pomegranate and strawberry juices could be due to differences in acidity (that acts synergistically with pressure in microbial inactivation) and initial microbial loads. In the context of high-acid foods, which includes pickled vegetables, contamination and spoilage is often caused by yeast and molds (Evelyn & Silva, 2019). Pickled radish processed at 550 MPa for 5 minutes resulted in a complete inactivation of yeasts and molds along with a 5.5-log CFU/ml reduction in the total plate count (Bao, Fan, Hu, Liao, & Chen, 2016).

Previous literature has demonstrated the preservation of pickled vegetables using HPP. Kimchi was processed at 500 MPa for 5 min at ambient temperature, with a come-up time of 1.7 min and decompression in < 10 seconds. This resulted in complete inactivation of murine norovirus-1 (Park et al., 2017). Whereas, sauerkraut was processed at 300 MPa for a holding time of 10 minutes at 40℃, with come-up and decompression times of 1-2 minutes. Microbial load reduction of 4-5 log in total aerobic mesophilic bacteria was achieved (Peñas, Frias, Gomez, & Vidal-Valverde, 2010). The Japanese fermented pickle made from the leaves of *Brassica campestris* L.var. rapifera, commonly called Nozawana-zuke, is highly perishable with a shelf life of only a few days even under refrigerated storage. High pressure processing of this pickle at 400 MPa (come-up time = 7.5 min and no holding time) and immediate decompression in 1 minute resulted in inactivation of LAB, gram negative bacteria, and fungi, showing some promise for improving storage life (Kuribayashi et al., 1996). However, there are still some challenges with processing using high pressure, as well as some opportunities for innovation.

1.5.2.3 Challenges and Opportunities

One of the main considerations when using HPP is the packaging – the material must be able to withstand the high pressure without any damage to the integrity, and at least one interface in the package needs to be flexible to transmit pressure from the hydraulic fluid to food (Juliano et al., 2010; Zhang et al., 2011). Products also undergo changes in volume during compression and release. In general, packaging for HPP should be able to accommodate a 15-20% reduction in volume without a compromise on the seal integrity and change in aesthetic qualities (Juliano et al., 2010). Polyethylene Terephthalate (PET), Ethylvinyl Alcohol (EVOH), and Polyvinyl Alcohol (PVA)-based flexible materials are commonly suitable for this purpose. Also, the headspace inside the package should be as minimal as possible. Air in the headspace can significantly increase the time taken for pressure development and creates problems of localized heating (Mújica-Paz, Valdez-Fragoso, Samson, Welti-Chanes, & Torres, 2011; Richter, Sterr, Jost, & Langowski, 2010). Most often, vegetable products are vacuum-packed before high pressure processing (Bao et al., 2016; Kamat, Dash, & Balasubramaniam, 2018; Park et al., 2017; Peñas et al., 2010; Sohn & Lee, 2002). Thus, flexibility, integrity, head space, along with stability, and favorable heat transfer characteristics are important technical criteria in selecting the packaging for HPP (Júnior, Cristianini, Padula, & Anjos, 2019). Prevention of compound migration from packaging into food is equally critical for HPP products to be safe for consumption, as changes in packaging material composition have been revealed in previous research (Bull, Steele, Kelly, Olivier, & Chapman, 2010; Galotto et al., 2010; Richter et al., 2010; Yoo, Sigua, Min, & Pascall, 2014). Glass jars, conventionally used by the pickle industry cannot be used for this process because of a lack of flexible interface between food and the pressure-transmitting fluid. But this technology allows for using many of the new flexible

packaging formats for pickled vegetables and provides an opportunity to reduce the high transportation costs associated with the use of glass jars.

While HPP has been capable in the inactivation of most vegetative cells of microorganisms, *Staphylococcus aureus* (Alpas et al., 1999) and some *E.coli* strains in high acid products (Cebrián, Mañas, & Condón, 2016), and spores such as those of *Clostridium botulinum* (Margosch et al., 2006; Margosch, Ehrmann, Gänzle, & Vogel, 2004; Ramaswamy, Shao, Bussey, & Austin, 2013) and *Bacillus sp.*(Reddy et al., 1999; Reineke, Mathys, & Knorr, 2011; Robertson, Carroll, & Pearce, 2008), have been found to be resistant to high pressures. HPP at ambient temperature does not inactivate the majority of microbial spores (Evelyn & Silva, 2019; Oh & Moon, 2003; Reddy et al., 1999; Reineke et al., 2011), but a combination of pressure and heat has proven effective in the inactivation of baroresistant organisms (Crawford, Murano, Olson, & Shenoy, 1996; Daryaei & Balasubramaniam, 2013; Daryaei, Balasubramaniam, & Legan, 2013; Margosch et al., 2006, 2004; Ramaswamy & Shao, 2010; Tola & Ramaswamy, 2014).

Vegetables and its products indigenously contain a plethora of enzymes such as pectinesterases (Bell, Etchells, & Jones, 1951), polygalacturonases (Bell, Etchells, & Jones, 1950; McFeeters, Bell, & Fleming, 1980; Saltveit & McFeeters, 1980), polyphenoloxidases (Tinello & Lante, 2018), peroxidases (Müftügil, 1985; Terefe, Buckow, & Versteeg, 2014), lipoxygenases (Baysal & Demirdöven, 2007; Terefe et al., 2014), cellulases, xylanases and glucanases, apart from other pectinolytic enzymes from fungal sources (Bell & Etchells, 1956; Etchells, Bell, Monroe, Masley, & Demain, 1958; Maruvada & McFeeters, 2009; Péréz-Diáz et al., 2013). Pressure can cause the denaturation and loss in functionality of enzymes by weakening of non-covalent linkages such as hydrogen bond, disulfide, linkages, and van der Waals forces in protein

structures (Terefe et al., 2014). It has been found that pressures above 300 MPa can cause irreversible changes in proteins at room temperature (Knorr, Heinz, & Buckow, 2006), but it is variable depending on the type and source of enzyme, pH, temperature, medium composition, and enzyme-substrate compartmentalization (Linda Ludikhuyze, Loey, Denys, & Hendrickx, 2002). Polyphenoloxidase (PPO), peroxidase (POD) and pectinmethylesterase (PME) in fruit and vegetable products are the most resistant to pressure and their sensitivity depends on their origin and the environment, while polygalacturonase (PG) and lipoxygenase (LOX) are relatively more sensitive to pressure (Terefe et al., 2014). With respect to PME inactivation, results have been variable in fruit and vegetable juices and purees – some have shown partial inactivation, while some others have shown increase in activity. For instance, partial inactivation (44-49%) occurred at pressures above 600 MPa (Castro, Loey, Saraiva, Smout, & Hendrickx, 2005; Castro, Loey, Saraiva, Smout, & Hendrickx, 2006), while increase in activity at increasing pressures was noted in carrot juice (Kim, Park, Cho, & Park, 2001). Results for PPO (Bayındırlı, Alpas, Bozoğlu, & Hızal, 2006; Butz et al., 1994; Gomes & Ledward, 1996; Kim et al., 2001; Matser, Knott, Teunissen, & Bartels, 2000; Plaza, Muñoz, Ancos, & Cano, 2003; Préstamo, Palomares, & Sanz, 2004; Weemaes et al., 1997) and POD (Plaza et al., 2003; Préstamo, Arabas, Fonberg-Broczek, & Arroyo, 2001; Préstamo et al., 2004) were similar, with no studies showing complete inactivation of any of these classes of enzymes. On the contrary, significant inactivation was observed in the case of LOX (Indrawati, Loey, Ludikhuyze, & Hendrickx, 1999; Y.-S. Kim et al., 2001; Loey, Ludikhuyze, & Hendrickx, 1999; L. Ludikhuyze, Broeck, Weemaes, & Hendrickx, 1998; Terefe et al., 2014). In another study, PPO and POD activities were found to be higher in pickled peppers, asparagus, and beets when processed at higher pressures of 600 MPa both at 45℃ as well as 65℃ (Kamat et al., 2018). Thus, the effect of pressure and pressure-

thermal treatments on enzymatic activities varies widely. The exact mechanism of enzyme inactivation by pressure, the required pressure intensities and process design for enzyme inactivation are not yet clearly understood. Due to incomplete inactivation of microbial spores and enzymes, most HPP products are stored under refrigeration.

In the context of pickled vegetables, PG is one of the most important causes for texture deterioration. Although HPP has shown varying extents of PG inactivation, the technology has been reported to improve texture. This has been demonstrated in pickled radish by the compression and collapse of cells due to pressure that resulted in a compact arrangement of cells as revealed by scanning electron microscopy (Bao et al., 2016). Such compaction could also result in color changes like a decrease in L* of pickled radish compared to untreated control (Bao et al., 2016) due to consequent reduction in internally scattered light (Macdougall, 2010). Similar improvement in texture (cutting force) but change in color has been observed in *Kimchi* (Sohn & Lee, 2002). Whether these changes in color are acceptable needs to be confirmed through sensory studies.

Beyond existing challenges, HPP has crossed the borders of solely being a technology for food preservation and quality improvement. The role of high pressure in rapid acid infusion into vegetable tissue can further help reduce processing times. The technology was used for more uniform and faster (4.7x) pH reduction by enabling rapid diffusion of acid to the core of carrot cubes, compared to a heat-assisted acidification (Tola & Ramaswamy, 2013). While this can contribute to a significant reduction in processing times in comparison to conventional methods, higher production costs (7x higher; $0.10 per liter of orange juice) and electricity consumption (3x higher; 1,000,000 kW/year) can be setbacks in the industrial adoption of HPP. Twin vessel systems has been proposed for increasing energy efficiencies in the process by employing the

energy released during decompression of the first vessel for the compression of the second pressure vessel (Rodriguez-Gonzalez et al., 2015). Despite these limitations, the water depletion and global warming potential of this technology is much lower than conventional thermal pasteurization as found by a lifecycle assessment (Pardo & Zufía, 2012). Increasing production volumes could help reduce costs (Sampedro, McAloon, Yee, Fan, & Geveke, 2014) and reduce environmental burden (Pardo & Zufía, 2012).

In summary, high pressure has been researched substantially in relation to the processing of fruit and vegetable products, and specifically composite products like pickled vegetables. Attributing to the higher nutritional and sensory quality, it can be a promising technology that is bound to grow steeply due to the high consumer impetus for health and clean label foods (Terefe et al., 2014).

1.6. CONCLUSION

More consumers have become conscious of what they eat and are demanding products with recognizable ingredients, processed in a sustainable manner, and labeled with honest information. This has led to the removal of unfamiliar or negatively perceived ingredients such as food additives and the search for new methods that will achieve the desired quality, safety, and shelf life with only 'clean' ingredients. Amongst many of the novel processing technologies, microwave and high-pressure processing have been widely adopted commercially. Apart from the improvements in microbiological, nutritional, and sensory qualities, both technologies show potential in sustainable food production as compared to conventional thermal processing. Figure 1.2 compares the operations involved in pasteurization by conventional and advanced processing technologies discussed above. This is mainly because these technologies rely less on non-renewable fossil fuels, have a reduced impact on global warming and use water at much lower

levels. This is not only important to satisfy growing ‘clean label’ demands, but adoption of such technologies is progress towards achieving global sustainability goals set by the United Nations. Though capital costs for both processing technologies are currently higher than conventional thermal processes currently, the cost-to-benefit ratio is bound to decrease with wider adoption and scaling-up of food production using such technologies. In relation to the production of pickled vegetables, these technologies present the potential to address the major problems of texture loss and shelf life faced by the industry, without the use of chemical additives. A recommended goal for future research with respect to environmental impact is to target reduction in the acidification and eutrophication potentials of these technologies by managing wastes from these processes responsibly (Pardo & Zufía, 2012).

TABLES

Table 1.1. Formulations and process variables of various pickled vegetables produced by the fresh pack process.

Vegetable	Pack out ratio (fruit/brine)	Typical Brine Composition*				Preservation process	References
		Acidulant	**Firming agent**	**Salt (NaCl)**	**Preservative/ Miscellaneous ingredients**		
Asparagus *(Asparagus officinalis)*	33% fruit/67% brine	Acetic acid 1-10%		1-6%	None or sodium benzoate = 1000 ppm	Pasteurization: 85°C, 30 minutes or 74°C, 15 minutes or HPP at 600 MPa, 5 minutes	Barreto, (2005); Fuleki, (1999); Kamat et al., (2018); Lau & Tang, (2002)
Beet *(Beta vulgaris)*		1% acetic acid				None or pasteurization at 85°C for 15 minutes	Bednar, Kies, & Carlson, (1991; Guldiken et al., (2016); Kosson, Elkner, & Szafirowska, (2011)
Cabbage *(Brassica oleracea)*		1.5% w/w citric acid			0.5% w/w Ethanol (flavoring agent)		Lonergan & Lindsay, (1979)
Carrot *(Daucus carota)*	35-65% vegetable/35 -65% brine	2.5% acetic acid (as white vinegar)				Pasteurization: 70°C for 12.45 minutes	Acosta, Vermeylen, Noel, & Padilla-Zakour, (2014)

Table 1.1 (continued). Formulations and process variables of various pickled vegetables produced by the fresh pack process.

Cucumber *(Cucumis sativus)*	50-60% fruit/40-50% brine	0.5-1.1% acetic acid and optionally other organic acids		2-4%		Pasteurization: 74°C, 15 minutes	Bell et al., (1972; Etchells & Jones, (1942); Fleming & McFeeters, (1981); McFeeters & Fleming, (1997); Monroe et al., (1969); Péréz-Diáz et al., (2013)
Green beans *(Phaseolus vulgaricus)*	50% vegetable/50 % brine	0.25% malic/citric/lactic acid or hydrochloric acid solution dosed to achieve a pH of 1.2-1.6				None or pasteurization in boiling water bath for 15 minutes	Basel, (1982, 1983); Kozup & Sistrunk, (1982)
Olive *(Olea europaea)*		Lactic acid 0.3-0.8% Acetic acid 0.3-1.2%	50-150 ppm (0.005-0.015%)	4-7%	Sorbate 0-500 ppm Benzoate 0-1000 ppm	-	Péréz-Diáz et al., (2013)

Table 1.1 (continued). Formulations and process variables of various pickled vegetables produced by the fresh pack process.

Peppers (*Capsicum annuum*) - Cherry pepper - Jalapeno pepper - Red bell pepper	35-60% fruit to 40-65% brine	Up to 3.67% acetic acid	0.2% as Calcium or ≥ 5mM CaCl2	0% - 7%	0 – 530 ppm sodium metabisulfite (preservative) and/or up to 12mM sodium benzoate	Pasteurization to an internal temperature of 67.1℃ - 92℃ for 10-30 minutes	Babanovska-Milenkovska et al., (2018); Breidt et al., (2007; Fleming et al., (1993); Gu et al., (1999); Guerra-vargas et al., (2001); Howard et al., 1994; McFeeters, (2004); Papageorge, McFeeters, & Fleming, (2003); Péréz-Díaz et al., (2013); Saldana & Meyer, (2006)

**All values are those in the equilibrated product.*

Table 1.2. Summary of previous literature on continuous flow microwave processing of fruit and vegetable products.

Product	Processing conditions				Effects on quality				Reference
	Frequ-ency	**Microw-ave power**	**Target temperatu-re, holding time**	**Tempera-ture after cooling**	**Microbiol-ogical**	**Enzyme activity**	**Nutritional**	**Sensory**	
Sweet potato puree (Orange-fleshed)	915 MHz	60 kW	135°C-145°C, 30 s	Ambient	- F_0 > 13 min - No viable counts after 90 d of ambient storage			Retention of viscosity	Coronel et al., (2005)
	915 MHz	60 kW	132°C, 25 s	Ambient [Precooling to 70°C-80°C in heat exchanger followed by cooling in ice bath]	> 4 log reduction of thermophilic spores of *Bacillus subtilis*, *Geobacillus stearothermophilus* using microbial indicator pouches				Brinley et al., (2007)

Table 1.2 (continued). Summary of previous literature on continuous flow microwave processing of fruit and vegetable products.

Sweet potato puree (Purple-fleshed)	915 MHz	60 kW	Preheating to 65C using heat exchanger, followed by MW heating at 135°C-145°C, 30 s	< 20°C	- $F_0 \geq 2.97$ min - Total plate counts: <1 CFU/30g - Thermophilic counts: <10 CFU/g		Increase in total phenols by 12% but significant decrease in anthocyanins	Significant changes in color (darkening) and consistency (gelation)	Steed et al., (2008)
Tomato juice	2450 MHz	18 kW	85°C, no holding	Ambient [Cooling using iced water]	No significant differences from conventionally pasteurized samples in total viable counts, Enterobacteriaceae, and lactic acid bacteria		Higher cytoprotective effect on Caco-2 intestinal cells against H_2O_2 - induced oxidative damage	- Hedonic test done with 28 assessors showed no differences in overall acceptability - Higher and more stable juice cloud compared to conventionally pasteurized samples	Stratakos et al., (2016)

Table 1.2 (continued). Summary of previous literature on continuous flow microwave processing of fruit and vegetable products.

Strawbe-rry puree	2450 MHz	20 kW	90C, 10 s	30°C	Total plate counts: 3-4 log CFU/ml Yeasts and molds: <1 log CFU/g	80% and 88% inactivation of PPO and POD respectively	- 93-96% retention of total phenolics - Key phenolic acids such as p-hydroxybenzoic acid and quercetin increased by 15-42% - Vitamin C retained = 96% - Anthocyanins retained up to 80%	- Significant changes in color measured instrumentally - Hedonic tests done but with small sample size (8 panelists)	Marszałek et al., (2015)

Table 1.2 (continued). Summary of previous literature on continuous flow microwave processing of fruit and vegetable products.

Orange juice	2450 MHz	570 W	70°C-92°C, 0-30 s	10°C [Refrigerated bath]	- Up to 6 log inactivation of *Lactobacillus plantarum* at 70°C, 15 s and 7 log reduction (<10 CFU/ml) at 80°C,15s - At 90°C, 30s no detectable counts (< 10 CFU/ml) were present	99% PME inactivation with MW and conventional thermal processing at 90°C, 30 s		- No difference detected among fresh, conventional, and microwave-processed samples on day 1 in a sensory triangle test	Nikdel, Chen, Parish, MacKellar, & Friedrich, (1993)
Kava juice	2450 MHz	330 W-550 W	41.4°C - 65.2°C		Up to 3.86 log reduction in total plate count	Up to 66% reduction in PME activity	No change or significant increase in DMY and K kavalactones	No visible starch gelling or loss of cloud	Abdullah et al., (2013)

FIGURES

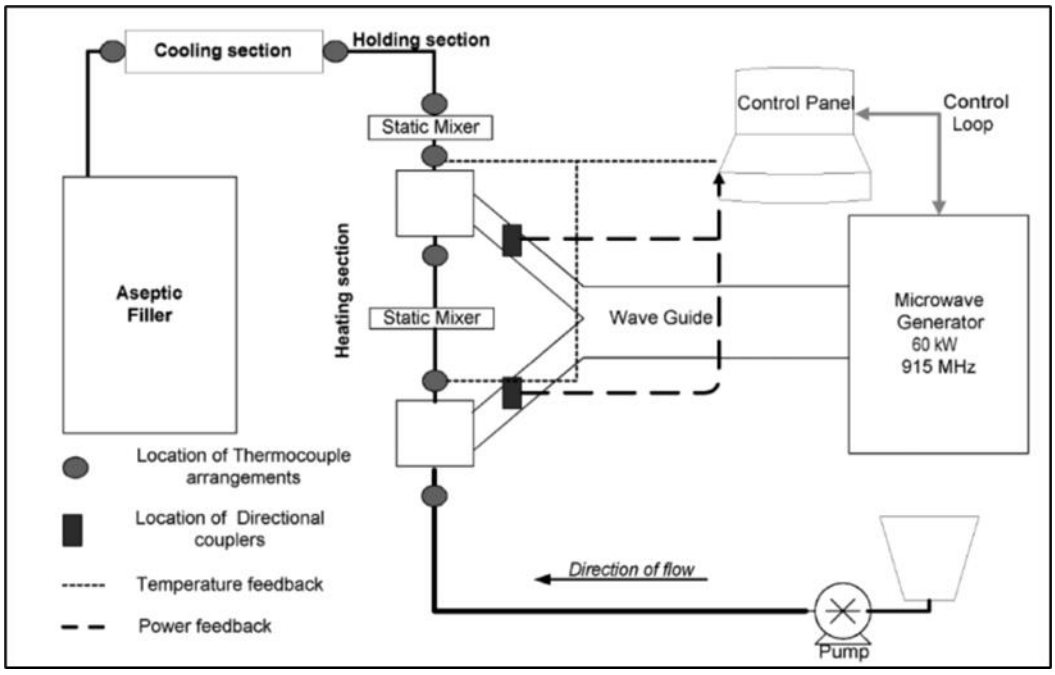

Figure 1.1 Schematic of the equipment setup adapted from Coronel et al. (2005)

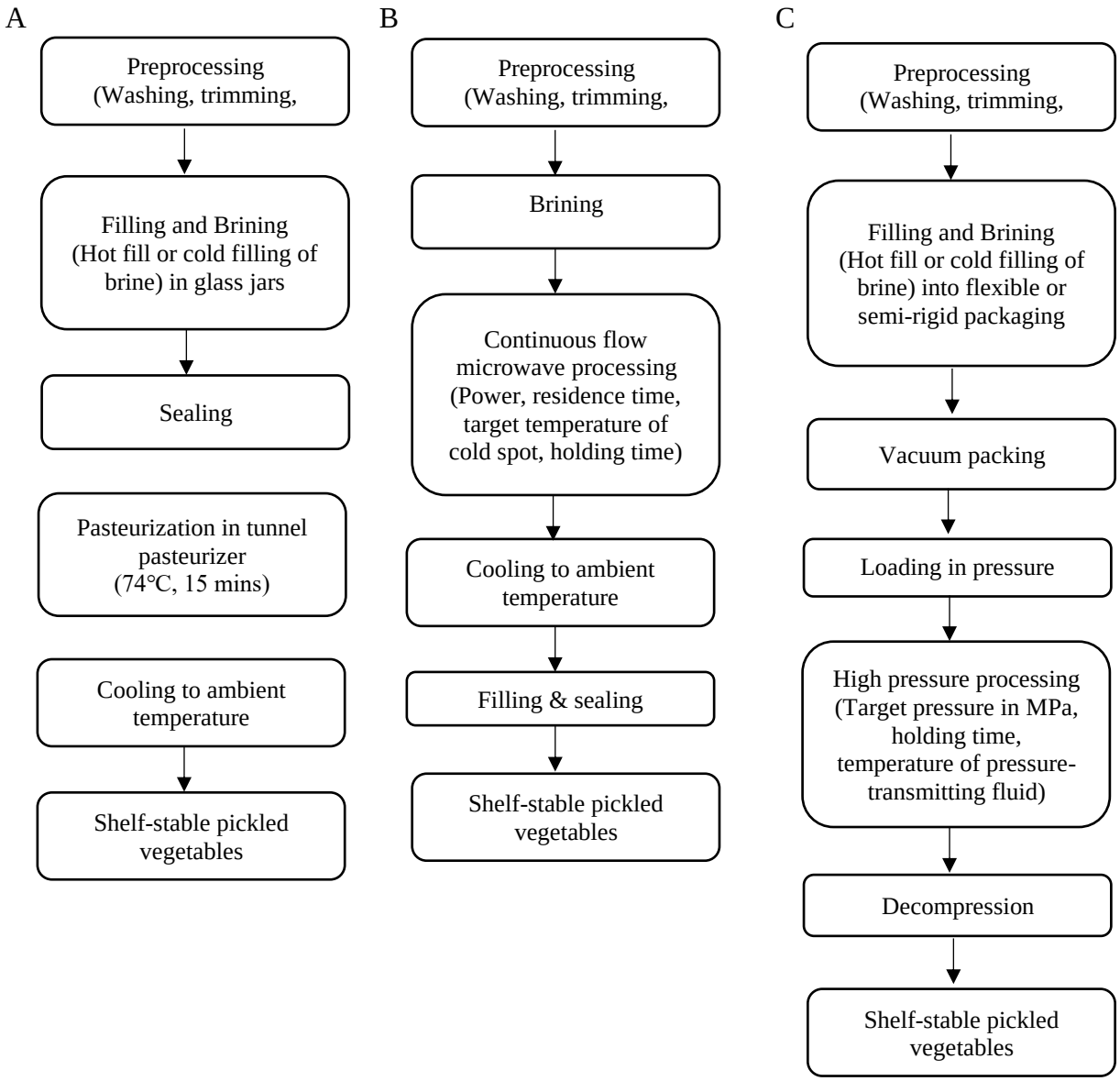

Figure 1.2: General process flowcharts comparing pasteurization using A) conventional process, B) microwave process, and C) high pressure process for pickled vegetables

REFERENCES

360 Market Updates. (2020, August 10). Global Pickles and Pickle Products Market Top Countries Data 2020 Industry Size, Future Trends, Growth Key Factors, Demand, Business Share, Sales & Income, Manufacture Players, Application, Scope, and Opportunities Analysis by Outlook. 360 Market Updates. Market research, . Retrieved from https://www.theexpresswire.com/pressrelease/Global-Pickles-and-Pickle-Products-Market-Top-Countries-Data-2020-Industry-Size-Future-Trends-Growth-Key-Factors-Demand-Business-Share-Sales-Income-Manufacture-Players-Application-Scope-and-Opportunities-Analysis-by-Outlook-By-360-Market-Updates_11447311

Aadil, R. M., Zeng, X.-A., Han, Z., & Sun, D.-W. (2013). Effects of ultrasound treatments on quality of grapefruit juice. Food Chemistry, 141(3), 3201–3206.

Abbaspourrad, A., Padilla-Zakour, O. I., Wiedmann, M., Moraru, C. I., & Goddard, J. M. (2017). Taking a Systems Approach to Clean Label Challenges. Food Technology, (November). Retrieved January 29, 2022, from https://www.ift.org/news-and-publications/food-technology-magazine/issues/2017/november/features/systems-approach-to-clean-label

Abdullah, S. A., Lee, S. H., Cho, I. K., Li, Q. X., Jun, S., & Choi, W. (2013). Pasteurization of kava juice using novel continuous flow microwave heating technique. Food Science and Biotechnology, 22(4), 961–966.

Abera, G. (2019). Review on high-pressure processing of foods. Cogent Food & Agriculture, 5(1).

Abid, M., Jabbar, S., Wu, T., Hashim, M. M., Hu, B., Lei, S., Zhang, X., et al. (2013). Effect of ultrasound on different quality parameters of apple juice. Ultrasonics Sonochemistry, 20(5), 1182–1187.

Acosta, O. G., Vermeylen, F. M., Noel, C., & Padilla-Zakour, O. I. (2014). Modeling the effects of process conditions on the accumulated lethality values of thermally processed pickled carrots. Food control, 51, 390–396.

Akdaş, Z. Z., & Bakkalbaşı, E. (2017). Influence of different cooking methods on color, bioactive compounds, and antioxidant activity of kale. International Journal of Food Properties, 20(4), 877–887. Taylor & Francis.

Albi, T., Lanzón, A., Guinda, A., León, M., & Pérez-Camino, M. C. (1997). Microwave and Conventional Heating Effects on Thermoxidative Degradation of Edible Fats. Journal of Agricultural and Food Chemistry, 45(10), 3795–3798. American Chemical Society.

Alpas, H., Kalchayanand, N., Bozoglu, F., Sikes, A., Dunne, C. P., & Ray, B. (1999). Variation in Resistance to Hydrostatic Pressure among Strains of Food-Borne Pathogens. Applied and Environmental Microbiology, 65(9), 4248–4251.

Ancos, B. de, Gonzalez, E., & Cano, M. P. (2000). Effect of High-Pressure Treatment on the Carotenoid Composition and the Radical Scavenging Activity of Persimmon Fruit Purees. Journal of Agricultural and Food Chemistry, 48(8), 3542–3548.

Arjmandi, M., Otón, M., Artés, F., Artés-Hernández, F., Gómez, P. A., & Aguayo, E. (2017). Microwave flow and conventional heating effects on the physicochemical properties, bioactive compounds and enzymatic activity of tomato puree. Journal of the Science of Food and Agriculture, 97(3), 984–990.

Aschemann-Witzel, J., Varela, P., & Peschel, A. odile. (2019). Consumers' categorization of food ingredients: Do consumers perceive them as 'clean label' producers expect? An exploration with projective mapping. Food Quality and Preference, 71, 117–128.

Asioli, D., Aschemann-Witzel, J., Caputo, V., Vecchio, R., Annunziata, A., Næs, T., & Varela, P. (2017). Making sense of the "clean label" trends: A review of consumer food choice behavior and discussion of industry implications. Food Research International, 99(Part 1), 58–71.

Babanovska-Milenkovska, F., Karakasova, L., Stojanova, M., Culeva, B., & Murkovic, M. (2018). Changes of nutritional properties of three variants pepper by processing of pickled red peppers. Journal of Agricultural, Food and Environmental Sciences, JAFES, 72(1), 52–58.

Balasubramanian, S., & Balasubramaniam, V. M. (2003). Compression heating influence of pressure transmitting fluids on bacteria inactivation during high pressure processing. Food Research International, 36(7), 661–668.

Balny, C., Mozhaev, V. V., & Lange, R. (1997). Hydrostatic Pressure and Proteins: Basic Concepts and New Data. Comparative Biochemistry and Physiology Part A: Physiology, 116(4), 299–304.

Bao, R., Fan, A., Hu, X., Liao, X., & Chen, F. (2016). Effects of high pressure processing on the quality of pickled radish during refrigerated storage. Innovative Food Science & Emerging Technologies, 38, 206–212.

Barreto, M. (2005). Causes and prevention of rutin (quercetin -3 -O -rhamnoglucoside) crystal deposition in pickled green asparagus (Asparagus officinalis) (PhD Thesis). Retrieved from https://search.proquest.com/docview/305027480/abstract/7F43F9118FE946B2PQ/1

Barth, M., Hankinson, T. R., Zhuang, H., & Breidt, F. (2009). Microbiological Spoilage of Fruits and Vegetables. In W. H. Sperber & M. P. Doyle (Eds.), Compendium of the Microbiological Spoilage of Foods and Beverages, Food Microbiology and Food Safety (pp. 135–183). New York, NY: Springer. Retrieved March 5, 2022, from https://doi.org/10.1007/978-1-4419-0826-1_6

Basel, R. M. (1982). Acidified Bulk Storage of Snap Beans and Peas. Journal of Food Science, 47(6), 2082–2083.

Basel, R. M. (1983). Technical note: The improvement of green colour of green beans by acidified bulk storage. International Journal of Food Science & Technology, 18(6), 797–799.

Bayındırlı, A., Alpas, H., Bozoğlu, F., & Hızal, M. (2006). Efficiency of high pressure treatment on inactivation of pathogenic microorganisms and enzymes in apple, orange, apricot and sour cherry juices. Food Control, 17(1), 52–58.

Baysal, T., & Demirdöven, A. (2007). Lipoxygenase in fruits and vegetables: A review. Enzyme and Microbial Technology, 40(4), 491–496.

Bazzani, C., Capitello, R., Ricci, E. C., Scarpa, R., & Begalli, D. (2019). Nutritional Knowledge and Health Consciousness: Do They Affect Consumer Wine Choices? Evidence from a Survey in Italy. Nutrients, 12(1), 84.

Bednar, C. M., Kies, C., & Carlson, M. (1991). Nitrate-nitrite levels in commercially processed and home processed beets and spinach. Plant foods for human nutrition (Dordrecht, Netherlands), 41(3), 261–268.

Begum, Y. A., & Deka, S. C. (2019). Effect of processing on structural, thermal, and physicochemical properties of dietary fiber of culinary banana bracts. Journal of Food Processing and Preservation, 43(12), e14256.

Bell, T. A., & Etchells, J. L. (1956). Pectin hydrolysis by certain salt-tolerant yeasts. Appl Microbiol., 4(4), 196–201.

Bell, T. A., Etchells, J. L., & Jones, I. D. (1950). Softening of commercial cucumber salt-stock in relation to polygalacturonase activity. Food Technol, 4(4), 157–163.

Bell, T. A., Etchells, J. L., & Jones, I. D. (1951). Pectinesterase in the cucumber. Arch Biochem Biophys., 31(3), 431–442.

Bell, T. A., Turney, L. J., & Etchells, J. L. (1972). Influence of different organic acids on the texture of fresh-pack pickles. Journal of Food Science, 37, 446–449.

Benlloch-Tinoco, M., Igual, M., Rodrigo, D., & Martínez-Navarrete, N. (2013). Comparison of microwaves and conventional thermal treatment on enzymes activity and antioxidant capacity of kiwifruit puree. Innovative Food Science & Emerging Technologies, 19, 166–172.

Bhat, R., Kamaruddin, N. S. B. C., Min-Tze, L., & Karim, A. A. (2011). Sonication improves kasturi lime (Citrus microcarpa) juice quality. Ultrasonics Sonochemistry, 18(6), 1295–1300.

Bhuwan Pandit, R., Tang, J., Liu, F., & Mikhaylenko, G. (2007). A computer vision method to locate cold spots in foods in microwave sterilization processes. Pattern Recognition, 40(12), 3667–3676.

Bomben, J. L., Ourkee, E. L., Lowe, E., & Secor, G. E. (1974). A Laboratory Study on Countercurrent Desalting of Pickles. Journal of Food Science, 39(2), 260–263.

Booth, I., & Stratford, M. (2003). Acidulants and low pH (pp. 25–47).

Breidt, F., Hayes, J. S., Osborne, J. A., & McFeeters, R. F. (2005). Determination of 5-Log Pathogen Reduction Times for Heat-Processed, Acidified Vegetable Brines. Journal of Food Protection, 68(2), 305–310.

Breidt, Fred, Hayes, J., & McFeeters, R. F. (2007). Determination of 5-Log Reduction Times for Food Pathogens in Acidified Cucumbers during Storage at 10 and 25°C. Journal of Food Protection, 70(11), 2638–2641.

Breidt, Frederick, Kay, K., Osborne, J., Ingham, B., & Arritt, F. (2014). Thermal Processing of Acidified Foods with pH 4.1 to pH 4.6. Food Protection Trends, 34(2), 132–138. Des Moines, United Kingdom: Allen Press Inc.

Brinley, T. A., Dock, C. N., Truong, V.-D., Coronel, P., Kumar, P., Simunovic, J., Sandeep, K. P., et al. (2007). Feasibility of Utilizing Bioindicators for Testing Microbial Inactivation in Sweetpotato Purees Processed with a Continuous-Flow Microwave System. Journal of Food Science, 72(5), E235–E242.

Brinley, T. A., Truong, V. D., Coronel, P., Simunovic, J., & Sandeep, K. P. (2008). Dielectric Properties of Sweet Potato Purees at 915 MHz as Affected by Temperature and Chemical Composition. International Journal of Food Properties, 11(1), 158–172. Taylor & Francis.

Brnawi, W. I., Hettiarachchy, N. S., Horax, R., Kumar-Phillips, G., Seo, H.-S., & Marcy, J. (2018). Comparison of Cinnamon Essential Oils from Leaf and Bark with Respect to Antimicrobial Activity and Sensory Acceptability in Strawberry Shake. Journal of Food Science, 83(2), 475–480.

Buescher, R., Cho, M. J., & Hamilton, C. (2013). Heat Conditioning of Cucumbers Improves Retention of Sliced Refrigerated Pickle Texture and Appearance. Journal of Food Biochemistry, 37(5), 564–570.

Buescher, R. W., Hudson, J. M., & Adams, J. R. (1979). Inhibition of Polygalacturonase Softening of Cucumber Pickles by Calcium Chloride. Journal of Food Science, 44(6), 1786–1787.

Buffler, C. R. (1993). Microwave cooking and processing: Engineering fundamentals for the food scientist. New York: New York : Van Nostrand Reinhold, [1993]. Retrieved from https://catalog.lib.ncsu.edu/catalog/NCSU810523

Bull, M., Steele, R., Kelly, M. S. A., Olivier, S., & Chapman, B. (2010). Packaging under pressure: Effects of high pressure, high temperature processing on the barrier properties of commonly available packaging materials. Innovative Food Science & Emerging Technologies, 11, 533–537.

Butz, P., Koller, W. D., Tauscher, B., & Wolf, S. (1994). Ultra-High Pressure Processing of Onions: Chemical and Sensory Changes. LWT - Food Science and Technology, 27(5), 463–467.

Campañone, L. A., Paola, C. A., & Mascheroni, R. H. (2012). Modeling and Simulation of Microwave Heating of Foods Under Different Process Schedules. Food and Bioprocess Technology, 5(2), 738–749.

Campbell-Platt, G., & Anderson, K. G. (1988). Pickles, Sauces and Salad Products. In M. D. Ranken (Ed.), Food Industries Manual. Reinhold: Van Nostrand.

Caponio, F., Pasqualone, A., & Gomes, T. (2003). Changes in the fatty acid composition of vegetable oils in model doughs submitted to conventional or microwave heating. International Journal of Food Science & Technology, 38(4), 481–486.

Cargill. (2017). Transparency and Simplicity: The New Normal in Product Development (Market research). Cargill Foods. Retrieved from https://www.cargill.com/doc/1432106811290/clean-label-white-paper.pdf

Castro, S., Loey, A. V., Saraiva, J., Smout, C., & Hendrickx, M. (2005). Process stability of Capsicum annuum pectin methylesterase in model systems, pepper puree and intact pepper tissue. European Food Research and Technology, 221(3), 452–458.

Castro, S. M., Loey, A. V., Saraiva, J. A., Smout, C., & Hendrickx, M. (2006). Identification of pressure/temperature combinations for optimal pepper (Capsicum annuum) pectin methylesterase activity. Enzyme and Microbial Technology, 38(6), 831–838.

Cebrián, G., Mañas, P., & Condón, S. (2016). Comparative Resistance of Bacterial Foodborne Pathogens to Non-thermal Technologies for Food Preservation. Frontiers in microbiology, 7, 734.

Chandrasekaran, S., Ramanathan, S., & Basak, T. (2012). Microwave material processing—A review. AIChE Journal, 58(2), 330–363.

Cha-um, W., Cha-um, W., Rattanadecho, P., Rattanadecho, P., Pakdee, W., & Pakdee, W. (2011). Experimental and Numerical Analysis of Microwave Heating of Water and Oil Using a Rectangular Wave Guide: Influence of Sample Sizes, Positions, and Microwave Power. Food and Bioprocess Technology, 4(4), 544–558.

Chen, D., Xi, H., Guo, X., Qin, Z., Pang, X., Hu, X., Liao, X., et al. (2013). Comparative study of quality of cloudy pomegranate juice treated by high hydrostatic pressure and high temperature short time. Innovative Food Science & Emerging Technologies, 19, 85–94.

Chen, W., & Hart, H. (2016). Consumers Turn an Eye to Clean Labels. Food Safety Magazine. Retrieved from https://www.foodsafetymagazine.com/magazine-archive1/octobernovember-2016/consumers-turn-an-eye-to-clean-labels/

Chen, X., Qin, W., Ma, L., Xu, F., Jin, P., & Zheng, Y. (2015). Effect of high pressure processing and thermal treatment on physicochemical parameters, antioxidant activity and volatile compounds of green asparagus juice. LWT - Food Science and Technology, Healthy Snacks: Recent Trends and Innovative Developments to Meet Current Needs, 62(1, Part 2), 927–933.

Cheng, C., Jia, M., Gui, Y., & Ma, Y. (2020). Comparison of the effects of novel processing technologies and conventional thermal pasteurisation on the nutritional quality and aroma of Mandarin (Citrus unshiu) juice. Innovative Food Science & Emerging Technologies, 64, 102425.

Cho, M. J., & Buescher, R. W. (2012). Potential Role of Native Pickling Cucumber Polygalacturonase in Softening of Fresh Pack Pickles. Journal of Food Science, 77(4), C443–C447.

Cho, W.-I., & Chung, M.-S. (2020). Improving the quality of vegetable foodstuffs by microwave inactivation. Food Science and Biotechnology, 29(1), 85–91.

Choi, W., Nguyen, L. T., Lee, S. H., & Jun, S. (2011). A Microwave and Ohmic Combination Heater for Uniform Heating of Liquid–Particle Food Mixtures. Journal of Food Science, 76(9), E576–E585.

Choi, Y., & Okos, M. (1986). Effects of temperature and composition on the thermal properties of food. In M. Le Maguer & P. Jelen (Eds.), Food Engineering and Process Applications: Transport Phenomena (Vol. 1, pp. 93–101). New York: Elsevier Applied Science Publishers.

Chun, O. K., Kim, D.-O., Smith, N., Schroeder, D., Han, J. T., & Lee, C. Y. (2005). Daily consumption of phenolics and total antioxidant capacity from fruit and vegetables in the American diet. Journal of the Science of Food and Agriculture, 85(10), 1715–1724.

Considine, K. M., Kelly, A. L., Fitzgerald, G. F., Hill, C., & Sleator, R. D. (2008). High-pressure processing – effects on microbial food safety and food quality. FEMS Microbiology Letters, 281(1), 1–9.

Coronel, P., Simunovic, J., & Sandeep, K. P. (2003). Temperature Profiles Within Milk after Heating in a Continuous-flow Tubular Microwave System Operating at 915 MHz. Journal of Food Science, 68(6), 1976–1981.

Coronel, Pablo, Truong, V.-D., Simunovic, J., Sandeep, K. P., & Cartwright, G. D. (2005). Aseptic Processing of Sweetpotato Purees Using a Continuous Flow Microwave System. Journal of Food Science, 70(9), E531–E536.

Crawford, Y. J., Murano, E. A., Olson, D. G., & Shenoy, K. (1996). Use of High Hydrostatic Pressure and Irradiation To Eliminate Clostridium sporogenes Spores in Chicken Breast. Journal of Food Protection, 59(7), 711–715.

Daryaei, H., & Balasubramaniam, V. M. (2013). Kinetics of Bacillus coagulans spore inactivation in tomato juice by combined pressure–heat treatment. Food Control, 30(1), 168–175.

Daryaei, H., Balasubramaniam, V. M., & Legan, J. D. (2013). Kinetics of Bacillus cereus Spore Inactivation in Cooked Rice by Combined Pressure–Heat Treatment. Journal of Food Protection, 76(4), 616–623.

De La Vega-Miranda, B., Santiesteban-López, N. A., López-Malo, A., & Sosa-Morales, M. E. (2012). Inactivation of Salmonella Typhimurium in fresh vegetables using water-assisted microwave heating. Food Control, 26(1), 19–22.

Dev, S. R. S., Raghavan, G. S. V., & Gariepy, Y. (2008). Dielectric properties of egg components and microwave heating for in-shell pasteurization of eggs. Journal of Food Engineering, 86(2), 207–214.

Devenyns, J. (2019). Onward and upward: Clean label trend shows no signs of slowing. Food Dive. Retrieved January 29, 2022, from https://www.fooddive.com/news/onward-and-upward-clean-label-trend-shows-no-signs-of-slowing/545738/

Drozd, J. Michael, & Joines, W. T. (2001, July 24). Electromagnetic exposure chamber with a focal region. Retrieved February 16, 2021, from https://patents.google.com/patent/US6265702B1/en

Drozd, James Michael, & Simunovic, J. (2017, July 25). Electromagnetic system. Retrieved February 16, 2021, from https://patents.google.com/patent/US9713340B2/en

EFSA CONTAM, Knutsen, H. K., Alexander, J., Barregård, L., Bignami, M., Brüschweiler, B., Ceccatelli, S., et al. (2017). Risks for public health related to the presence of furan and methylfurans in food. EFSA Journal, 15(10), e05005.

Ekpunobi, U. E., Ukatu, S. C., Ngene, B. O., Onyema, C. T., & Ofora, P. U. (2014). Investigation of the thermal properties of selected fruits and vegetables. American Journal of Science and Technology, 1(5), 293–297.

Etchells, J. L., Bell, T. A., Monroe, R. J., Masley, P. M., & Demain, A. L. (1958). Populations and Softening Enzyme Activity of Filamentous Fungi on Flowers, Ovaries, and Fruit of Pickling Cucumbers. Applied Microbiology, 6(6), 427–440.

Etchells, J. L., & Jones, I. D. (1942). Pasteurization of pickle products. The Fruit Product Journal, 21(11), 330–332.

Evelyn, & Silva, F. V. M. (2019). Heat assisted HPP for the inactivation of bacteria, moulds and yeasts spores in foods: Log reductions and mathematical models. Trends in Food Science & Technology, 88, 143–156.

FAO. (2011). Global food losses and food waste: Extent, causes and prevention. Rome. Retrieved from http://www.fao.org/3/mb060e/mb060e.pdf

Farr, D. (1990). High pressure technology in the food industry. Trends in Food Science & Technology, 1, 14–16.

FDA. (2004). Acidified Foods. C.F.R. (Vol. 21). Retrieved April 24, 2022, from https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=114&showFR=1

FDA. (2019). Acidified Foods. Retrieved from https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=114&showFR=1

Fernandez, A., Butz, P., Bognàr, A., & Tauscher, B. (2001). Antioxidative capacity, nutrient content and sensory quality of orange juice and an orange-lemon-carrot juice product after high pressure treatment and storage in different packaging. European Food Research and Technology, 213, 290–296.

Ferrari, G., & Matteo, M. D. (1996). High pressure stabilization of orange juice: Evaluation of the effects of process conditions. Italian Journal of Food science., 8(2), 99–106.

Ferreira, M., Pereira, S., Almeida, A., Queirós, R., Delgadillo, I., Saraiva, J., & Cunha, A. (2015). Effect of temperature and compression/decompression rates on high pressure inactivation of Listeria. Acta Alimentaria. Retrieved from https://www.researchgate.net/publication/273335227_Effect_of_temperature_and_compressiondecompression_rates_on_high_pressure_inactivation_of_Listeria

Fleming, H., McFeeters, R., & Breidt, F. (2001). Fermented and Acidified Vegetables. Compendium of Methods for The Microbiological Examination of Foods (pp. 521–532). Washington DC: American Public Health Association.

Fleming, H. p., Daeschel, M. a., McFEETERS, R. f., & Pierson, M. d. (1989). Butyric Acid Spoilage of Fermented Cucumbers. Journal of Food Science, 54(3), 636–639.

Fleming, H. P., & McFeeters, R. F. (1981). Shelf life of fresh-pack cucumber pickles. St.Charles, IL: Advisory statement published and distributed by Pickle Packers International, Inc.

Fleming, H. P., McFeeters, R. F., Daeschel, M. A., Humphries, E. G., & Thompson, R. L. (1988). Fermentation of Cucumbers in Anaerobic Tanks. Journal of Food Science, 53(1), 127–133.

Fleming, H. P., McFeeters, R. F., & Thompson, R. I. (1987). Effects of Sodium Chloride Concentration on Firmness Retention of Cucumbers Fermented and Stored with Calcium Chloride. Journal of Food Science, 52(3), 653–657.

Fleming, H. P., Thompson, R. L., & McFeeters, R. F. (1993). Firmness Retention in Pickled Peppers as Affected by Calcium Chloride, Acetic Acid, and Pasteurization. Journal of Food Science, 58(2), 325–330.

Fleming, H. P., Thompson, R. L., & McFeeters, R. F. (1996). Assuring Microbial and Textural Stability of Fermented Cucumbers by pH Adjustment and Sodium Benzoate Addition. Journal of Food Science, 61(4), 832–836.

Fleming, Henry P. (1984). Developments in cucumber fermentation. Journal of Chemical Technology and Biotechnology. Biotechnology, 34(4), 241–252.

Food Navigator. (2017). “GoCleanLabel certified” scheme rolls out, but what does it mean? Foodnavigator-usa.com. Retrieved January 29, 2022, from https://www.foodnavigator-usa.com/Article/2017/06/13/GoCleanLabel-certified-scheme-rolls-out-but-what-does-it-mean

Forgrieve, J. (2018). How food makers, restaurant chains are cleaning up their labels. SmartBrief. Retrieved January 29, 2022, from https://corp.smartbrief.com/original/2018/09/how-food-makers-restaurant-chains-are-cleaning-their-labels

Franco, W., Pérez-Díaz, I. M., Johanningsmeier, S. D., & McFeeters, R. F. (2012). Characteristics of Spoilage-Associated Secondary Cucumber Fermentation. Applied and Environmental Microbiology, 78(4), 1273–1284.

Fuleki, T. (1999). Rutin, The Main Component of Surface Deposits on Pickled Green Asparagus. Journal of Food Science, 64(2), 252–254.

Galarza, D. (2015, June 4). Subway Will Drop Artificial Ingredients by 2017. Eater. Retrieved January 29, 2022, from https://www.eater.com/2015/6/4/8727495/subway-will-drop-artificial-ingredients-by-2017

Galotto, M. J., Ulloa, P., Escobar, R., Guarda, A., Gavara, R., & Miltz, J. (2010). Effect of high-pressure food processing on the mass transfer properties of selected packaging materials. Packaging Technology and Science, 23(5), 253–266.

Garcia, A. F., Butz, P., & Tauscher, B. (2001). Effects of High-pressure Processing on Carotenoid Extractability, Antioxidant Activity, Glucose Diffusion, and Water Binding of Tomato Puree (Lycopersicon esculentum Mill.). Journal of Food Science, 66(7), 1033–1038.

Gentry, T. S., & Roberts, J. S. (2005). Design and evaluation of a continuous flow microwave pasteurization system for apple cider. LWT - Food Science and Technology, 38(3), 227–238.

George, J. (2016, February 27). Consumers in Charge as Mars Finally Submits to Artificial…. Euromonitor. Retrieved January 29, 2022, from https://www.euromonitor.com/article/consumers-charge-mars-finally-submits-artificial-colour-demands

Ghnimi, S., & Guizani, N. (2018). Vegetable Fermentation and Pickling. In M. Siddiq & M. A. Uebersax (Eds.), Handbook of Vegetables and Vegetable Processing (2nd ed., pp. 407–427). John Wiley & Sons Ltd. Retrieved from https://onlinelibrary-wiley-com.prox.lib.ncsu.edu/doi/10.1002/9781119098935.ch17

Giuliani, R., Bevilacqua, A., Corbo, M. R., & Severini, C. (2010). Use of microwave processing to reduce the initial contamination by Alicyclobacillus acidoterrestris in a cream of asparagus and effect of the treatment on the lipid fraction. Innovative Food Science & Emerging Technologies, 11(2), 328–334.

Gomes, M. R. A., & Ledward, D. A. (1996). Effect of high-pressure treatment on the activity of some polyphenoloxidases. Food Chemistry, 56(1), 1–5.

Gong, Y., Yu, J.-Y., Qian, P., Meng, J., Zhang, X.-J., & Lu, R.-R. (2015). Comparative Study of the Microbial Stability and Quality of Carrot Juice Treated by High-Pressure Processing Combined with Mild Temperature and Conventional Heat Treatment. Journal of Food Process Engineering, 38(4), 395–404.

Goyal, S. K. (2006). Potential in Agribusiness—Fruit and Vegetable Processing Industry in India. Journal of International Farm Management, 3(2).

Gu, Y. S., Howard, L. R., & Wagner, A. B. (1999). Firmness and Cell Wall Characteristics of Pasteurized Jalapeño Pepper Rings as Affected by Calcium Chloride and Rotary Processing. Journal of Food Science, 64(3), 494–497.

Guerra-vargas, M., Jaramillo-flores, M. E., Dorantes-alvarez, L., & Hernández-sánchez, H. (2001). Carotenoid Retention In Canned Pickled Jalapeño Peppers and Carrots As Affected by Sodium Chloride, Acetic Acid, and Pasteurization. Journal of Food Science, 66(4), 620–626.

Guerrouj, K., Sánchez-Rubio, M., Taboada-Rodríguez, A., Cava-Roda, R. M., & Marín-Iniesta, F. (2016). Sonication at mild temperatures enhances bioactive compounds and microbiological quality of orange juice. Food and Bioproducts Processing, 99, 20–28.

Guillou, A. A., Floros, J. D., & Cousin, M. A. (1992). Calcium Chloride and Potassium Sorbate Reduce Sodium Chloride used during Natural Cucumber Fermentation and Storage. Journal of Food Science, 57(6), 1364–1368.

Guillou, Anne A., & Floros, J. D. (1992). Problems Associated With the Processing of Cucumber Pickles: Softening, Bloater Formation and Environmental Pollution. In G. Charalambous (Ed.), Developments in Food Science (Vol. 29, pp. 499–514). Elsevier. Retrieved from http://www.sciencedirect.com/science/article/pii/B9780444888341500442

Guldiken, B., Toydemir, G., Memis, K. N., Okur, S., Boyacioglu, D., & Capanoglu, E. (2016). Home-Processed Red Beetroot (Beta vulgaris L.) Products: Changes in Antioxidant Properties and Bioaccessibility. International Journal of Molecular Sciences, 17(6), 858.

Gutierrez, J., Bourke, P., Lonchamp, J., & Barry-Ryan, C. (2009). Impact of plant essential oils on microbiological, organoleptic and quality markers of minimally processed vegetables. Innovative Food Science & Emerging Technologies, 10(2), 195–202.

Hassanein, M. M., El-Shami, S. M., & El-Mallah, M. H. (2003). Changes occurring in vegetable oils composition due to microwave heating. Grasas y Aceites, 54(4), 343–349.

Heddleson, R. A., & Doores, S. (1994). Factors Affecting Microwave Heating of Foods and Microwave Induced Destruction of Foodborne Pathogens – A Review. Journal of Food Protection, 57(11), 1025–1037.

Hollis, F. H., Denney, S., Halfacre, J., Jackson, T., Link, A., & Orr, D. (2020). Human perception of fresh produce treated with grape seed extract: A preliminary study. Journal of Sensory Studies, 35(2), e12554.

Howard, L. R., Burma, P., & Wagner, A. B. (1994). Firmness and Cell Wall Characteristics of Pasteurized Jalapeño Pepper Rings Affected by Calcium Chloride and Acetic Acid. Journal of Food Science, 59(6), 1184–1186.

Hradecky, J., Kludska, E., Belkova, B., Wagner, M., & Hajslova, J. (2017). Ohmic heating: A promising technology to reduce furan formation in sterilized vegetable and vegetable/meat baby foods. Innovative Food Science & Emerging Technologies, 43, 1–6.

Huang, H.-W., Wu, S.-J., Lu, J.-K., Shyu, Y.-T., & Wang, C.-Y. (2017). Current status and future trends of high-pressure processing in food industry. Food Control, 72, 1–8.

Hunter, R. W., Dhaun, N., & Bailey, M. A. (2022). The impact of excessive salt intake on human health. Nature Reviews Nephrology, 1–15. Nature Publishing Group.

Indrawati, I., Loey, A. M. V., Ludikhuyze, L. R., & Hendrickx, M. E. (1999). Single, combined, or sequential action of pressure and temperature on lipoxygenase in green beans (Phaseolus vulgaris L.): A kinetic inactivation study. Biotechnology Progress, 15(2), 273–277.

Iwassa, I. J., Piai, J. F., & Bolanho, B. C. (2019). Fiber concentrates from asparagus by-products: Microstructure, composition, functional and antioxidant properties. Ciência e Agrotecnologia, 43. Editora da UFLA. Retrieved February 1, 2022, from http://www.scielo.br/j/cagro/a/scRB79K8yBYNx8GXx6tTzNF/?lang=en&format=html

Jabbar, S., Abid, M., Wu, T., Muhammad Hashim, M., Hu, B., Lei, S., Zhu, X., et al. (2014). Study on combined effects of blanching and sonication on different quality parameters of carrot juice. International Journal of Food Sciences and Nutrition, 65(1), 28–33. Taylor & Francis.

Jermann, C., Koutchma, T., Margas, E., Leadley, C., & Ros-Polsk, V. (2015). Mapping trends in novel and emerging food processing technologies around the world. Innovative Food Science & Emerging Technologies, 31, 14–27.

Jiang, H., Liu, Z., & Wang, S. (2017). Microwave processing: Effects and impacts on food components. Critical Reviews in Food Science and Nutrition, 58(14), 2476–2489. Taylor & Francis.

Johanningsmeier, S., Thompson, R. L., & Fleming, H. (2003). Bag-in-box technology: Sensory quality of pickles produced from process-ready, fermented cucumbers. Pickle Pak Sci, 8.

Juliano, P., Koutchma, T., Sui, Q., Barbosa-Canovas, G. V., & Sadler, G. (2010). Polymeric-Based Food Packaging for High-Pressure Processing. Food Engineering Reviews, 2, 274–297.

Jun, S., & Puri, V. M. (2004). DEVELOPMENT OF INTERACTIVE COMPUTATIONAL MODEL OF TEMPERATURE AND MOISTURE DISTRIBUTIONS OF MICROWAVED FOODS. Applied Engineering in Agriculture, 20(5), 677–682.

Júnior, L. M., Cristianini, M., Padula, M., & Anjos, C. A. R. (2019). Effect of high-pressure processing on characteristics of flexible packaging for foods and beverages. Food Research International, 119, 920–930.

Kaack, K. V. (2017). Industrial Processing of Pickled and Pasteurized Onion (Allium Cepa L.). International Journal of Forestry and Horticulture, 3(2), 35–45.

Kalchayanand, N., Frethem, C., Dunne, P., Sikes, A., & Ray, B. (2002). Hydrostatic pressure and bacteriocin-triggered cell wall lysis of Leuconostoc mesenteroides. Innovative Food Science & Emerging Technologies, 3(1), 33–40.

Kalsec. (2019). Consumer Trends: Clean and Clear Labels (Market research). Kalsec Inc. Retrieved from https://info.kalsec.com/consumer-trends-clean-and-clear-labels

Kamat, S. S., Dash, K. K., & Balasubramaniam, V. M. (2018). Quality changes in combined pressure-thermal treated acidified vegetables during extended ambient temperature storage. Innovative Food Science & Emerging Technologies, 49, 146–157.

Kamp, K. (2019). CONDIMENTS - US - NOVEMBER 2019. Mintel Group Ltd. Retrieved from http://academic.mintel.com/sinatra/oxygen_academic/display/id=919256

Katz, B. (2011, December 1). Cleaning Up Processed Foods. Food Technology, 65(12). Retrieved from https://www.ift.org/news-and-publications/food-technology-magazine/issues/2011/december/features/cleaning-up-processed-foods

Kerry. (2019). Future of Food (Market research). Kerry Group. Retrieved from https://kerry.com/na-en/explore/future-of-food-white-paper

Khouryieh, H. A. (2021). Novel and emerging technologies used by the U.S. food processing industry. Innovative Food Science & Emerging Technologies, 67, 102559.

Kim, J. Y., Han, S. J., Whang, L., Lee, J. H., Choi, I.-L., & Kang, H.-M. (2019). Effects of Chlorine Water and Plasma Gas Treatments on the Quality and Microbial Control of Latuca indica L. Baby Leaf Vegetable during MA Storage. Journal of Bio-Environment Control, 28(3), 197–203. The Korean Society for Bio-Environment Control.

Kim, Y.-S., Park, S.-J., Cho, Y.-H., & Park, J. (2001). Effects of Combined Treatment of High Hydrostatic Pressure and Mild Heat on the Quality of Carrot Juice. Journal of Food Science, 66(9), 1355–1360.

Knoerzer, K., Buckow, R., Sanguansri, P., & Versteeg, C. (1982). Adiabatic compression heating coefficients for high-pressure processing of water, propylene-glycol and mixtures – A combined experimental and numerical approach. Journal of food engineering, 96(2), 229–238.

Knorr, D., Heinz, V., & Buckow, R. (2006). High pressure application for food biopolymers. Biochimica et Biophysica Acta (BBA)—Proteins and Proteomics, 1764(3), 619–631.

Koskiniemi, C. B., Truong, V.-D., McFeeters, R. F., & Simunovic, J. (2013). Quality evaluation of packaged acidified vegetables subjected to continuous microwave pasteurization. LWT - Food Science and Technology, 54(1), 157–164.

Koskiniemi, C. B., Truong, V.-D., Simunovic, J., & McFeeters, R. F. (2011). Improvement of heating uniformity in packaged acidified vegetables pasteurized with a 915MHz continuous microwave system. Journal of Food Engineering, 105(1), 149–160.

Koskiniemi, C., Truong, V. D., McFeeters, R., & Simunovic, J. (2012). Effects of Acid, Salt and Soaking Time on the Dielectric Properties of Acidified Vegetables. International Journal of Food Properties—INT J FOOD PROP, 16(4). Retrieved from https://www.researchgate.net/publication/239799939_Effects_of_Acid_Salt_and_Soaking_Time_on_the_Dielectric_Properties_of_Acidified_Vegetables

Kosson, R., Elkner, K., & Szafirowska, A. (2011). Quality of Fresh and Processed Red Beet from Organic and Conventional Cultivation. Vegetable Crops Research Bulletin, 75. Retrieved from https://www.researchgate.net/publication/272667365_Quality_of_Fresh_and_Processed_Red_Beet_from_Organic_and_Conventional_Cultivation

Kozup, J., & Sistrunk, W. A. (1982). Quality Attributes of Fermented and Acidified Green Beans. Journal of Food Science, 47(3), 1001–1005.

Krebbers, B., Matser, A. M., Koets, M., & Berg, R. W. V. den. (2002). Quality and storage-stability of high-pressure preserved green beans. Journal of Food Engineering, 54(1), 27–33.

Kumar, P., Coronel, P., Simunovic, J., Truong, V. D., & Sandeep, K. P. (2007). Measurement of Dielectric Properties of Pumpable Food Materials under Static and Continuous Flow Conditions. Journal of Food Science, 72(4), E177–E183.

Kumar, P., Coronel, P., Truong, V. D., Simunovic, J., Swartzel, K. R., Sandeep, K. P., & Cartwright, G. (2008). Overcoming issues associated with the scale-up of a continuous flow microwave system for aseptic processing of vegetable purees. Food Research International, 41(5), 454–461.

Kuribayashi, T., Ohsawa, K., Takanami, S., & Kurokouchi, K. (1996). High pressure treatment for Nozawana-zuke (salted vegetables) preservation. In R. Hayashi & C. Balny (Eds.), Progress in Biotechnology (Vol. 13, pp. 397–400). Elsevier. Retrieved from http://www.sciencedirect.com/science/article/pii/S0921042306800675

Lau, M. H., & Tang, J. (2002). Pasteurization of pickled asparagus using 915 MHz microwaves. Journal of Food Engineering, 51(4), 283–290.

Laurita, R., Gozzi, G., Tappi, S., Capelli, F., Bisag, A., Laghi, G., Gherardi, M., et al. (2021). Effect of plasma activated water (PAW) on rocket leaves decontamination and nutritional value. Innovative Food Science & Emerging Technologies, 73, 102805.

Lee, S.-Y. (2004). Microbial Safety of Pickled Fruits and Vegetables and Hurdle Technology. Int. J. Food Safety, 4, 21–32.

Liu, F., Zhang, X., Zhao, L., Wang, Y., & Liao, X. (2016). Potential of high-pressure processing and high-temperature/short-time thermal processing on microbial, physicochemical and sensory

assurance of clear cucumber juice. Innovative Food Science & Emerging Technologies, 34, 51–58.

Llorca, E., Puig, A., Hernando, I., Salvador, A., Fiszman, S. M., & Lluch, M. A. (2001). Effect of fermentation time on texture and microstructure of pickled carrots. Journal of the Science of Food and Agriculture, 81(15), 1553–1560.

Loey, A. M. V., Ludikhuyze, L. R., & Hendrickx, M. E. (1999). Soybean Lipoxygenase Inactivation by Pressure at Subzero and Elevated Temperatures. Journal of Agricultural and Food Chemistry, 47(6), 2468–2474.

Lonergan, D., & Lindsay, R. C. (1979). Evaluation of Sauerkraut-Like Products From Direct-Acidification of Cabbage. Journal of Food Protection, 42(1), 38–42.

Lu, Z., Pérez-Díaz, I. M., Hayes, J. S., & Breidt, F. (2020). Bacteriophages Infecting Gram-Negative Bacteria in a Commercial Cucumber Fermentation. Frontiers in Microbiology, 11. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7332585/

Ludikhuyze, L., Broeck, I. V. den, Weemaes, C., & Hendrickx, M. (1998). Effect of Combined Pressure and Temperature on Soybean Lipoxygenase. 2. Modeling Inactivation Kinetics under Static and Dynamic Conditions. Journal of Agricultural and Food Chemistry, 46(10), 4081–4086.

Ludikhuyze, Linda, Loey, A. van, Denys, S., & Hendrickx, M. (2002). Effects of High Pressure on Enzymes Related to Food Quality. Ultra High Pressure Treatments of Foods (pp. 115–166).

Macdougall, D. B. (2010). Colour measurement of food: Principles and practice. In M. L. Gulrajani (Ed.), Colour Measurement: Principles, Advances and Industrial Applications (pp. 312–342). Woodhead Publishing. Retrieved from http://www.sciencedirect.com/science/article/pii/B9781845695590500121

Mackenzie, M. (2017). Certified CLEAN and RAW Food Labels Are About to Change the Way You Grocery Shop. Shape. Retrieved January 29, 2022, from https://www.shape.com/healthy-eating/diet-tips/whats-certified-clean-certified-raw

Margosch, D., Ehrmann, M. A., Buckow, R., Heinz, V., Vogel, R. F., & Gänzle, M. G. (2006). High-pressure-mediated survival of Clostridium botulinum and Bacillus amyloliquefaciens endospores at high temperature. Applied and Environmental Microbiology, 72(5), 3476–3481.

Margosch, D., Ehrmann, M. A., Gänzle, M. G., & Vogel, R. F. (2004). Comparison of pressure and heat resistance of Clostridium botulinum and other endospores in mashed carrots. Journal of Food Protection, 67(11), 2530–2537.

Marszałek, K., Mitek, M., & Skąpska, S. (2015). Effect of Continuous Flow Microwave and Conventional Heating on the Bioactive Compounds, Colour, Enzymes Activity, Microbial and Sensory Quality of Strawberry Purée. Food and Bioprocess Technology, 8(9), 1864–1876.

Maruvada, R., & McFeeters, R. F. (2009). Evaluation of enzymatic and non-enzymatic softening in low salt cucumber fermentations. International Journal of Food Science & Technology, 44(6), 1108–1117.

Matser, A., Knott, E., Teunissen, P., & Bartels, P. (2000). Effects of high isostatic pressure on mushrooms. Journal of Food Engineering 45 (1):11-16, 45. Retrieved from 10.1016/S0260-8774(00)00035-2

McFeeters, R. F. (2004). Fermentation Microorganisms and Flavor Changes in Fermented Foods. Journal of Food Science, 69(1), FMS35–FMS37.

McFeeters, R. F., Bell, T. A., & Fleming, H. P. (1980). An endo-polygalacturonase in cucumber fruit. J Food Biochem, 4(1), 1–16.

McFEETERS, R. F., & Fleming, H. P. (1991). PH Effect on Calcium Inhibition of Softening of Cucumber Mesocarp Tissue. Journal of Food Science, 56(3), 730–732.

McFeeters, R. F., & Fleming, H. P. (1997). Balancing macromineral composition of fresh-pack cucumber pickles to improve nutritional quality and maintain flavor. J Food Qual, 20(1), 81–89.

McHugh, T. (2016). Microwave Processing Heats Up. Food Technology, 70(10). Retrieved from https://www.ift.org/news-and-publications/food-technology-magazine/issues/2016/october/columns/processing-microwave-heating-applications-in-the-food-industry

Mclnerney, J. K., Seccafien, C. A., Steward, C. M., & Bird, A. R. (2007). Effects of high pressure processing on antioxidant activity, and total carotenoid content and availability, in vegetables. Innovative Food Science & Emerging Technologies, 8(4), 543–548.

McMurtrie, E. K., & Johanningsmeier, S. D. (2018). Quality of Cucumbers Commercially Fermented in Calcium Chloride Brine without Sodium Salts. Journal of Food Quality, 2018. Retrieved from https://www.hindawi.com/journals/jfq/2018/8051435/

Medina-Meza, I. G., Barnaba, C., Villani, F., & Barbosa-Cánovas, G. V. (2015). Effects of thermal and high pressure treatments in color and chemical attributes of an oil-based spinach sauce. LWT - Food Science and Technology, 60(1), 86–94.

Min, S. C., Roh, S. H., Niemira, B. A., Boyd, G., Sites, J. E., Fan, X., Sokorai, K., et al. (2018). In-package atmospheric cold plasma treatment of bulk grape tomatoes for microbiological safety and preservation. Food Research International, 108, 378–386.

Monroe, R. J., Etchells, J. L., Pacilio, J. C., Borg, A. F., Wallace, D. H., Rogers, M. P., Turney, L. J., et al. (1969). Influence of various acidities and pasteurizing temperatures on the keeping quality of fresh-pack dill pickles. Food Technology, 23(1), 71–77.

Müftügil, N. (1985). The peroxidase enzyme activity of some vegetables and its resistance to heat. Journal of the Science of Food and Agriculture, 36(9), 877–880.

Mújica-Paz, H., Valdez-Fragoso, A., Samson, C., Welti-Chanes, J., & Torres, J. (2011). High-Pressure Processing Technologies for the Pasteurization and Sterilization of Foods. Food and Bioprocess Technology, 4(6), 969–985.

Munir, M., Nadeem, M., Qureshi, T. M., Leong, T. S. H., Gamlath, C. J., Martin, G. J. O., & Ashokkumar, M. (2019). Effects of high pressure, microwave and ultrasound processing on proteins and enzyme activity in dairy systems—A review. Innovative Food Science & Emerging Technologies, 57, 102192.

Nestle. (2015, February 17). Nestlé USA Commits to Removing Artificial Flavors and FDA-Certified Colors from All Nestlé Chocolate Candy by the End of 2015. Retrieved January 29, 2022, from https://www.businesswire.com/news/home/20150217005211/en/Nestl%C3%A9-USA-Commits-to-Removing-Artificial-Flavors-and-FDA-Certified-Colors-from-All-Nestl%C3%A9-Chocolate-Candy-by-the-End-of-2015

Neudorf, S. (2015). Kellogg's to Eliminate Artificial Flavors and Colors by 2018. The Daily Meal. Retrieved January 29, 2022, from https://www.thedailymeal.com/news/eat/kellogg-s-eliminate-artificial-flavors-and-colors-2018/080515

Nguyen, L. T., Choi, W., Lee, S. H., & Jun, S. (2013). Exploring the heating patterns of multiphase foods in a continuous flow, simultaneous microwave and ohmic combination heater. Journal of Food Engineering, 116(1), 65–71.

Nguyen, L. T., Tay, A., Balasubramaniam, V. M., Legan, J. D., Turek, E. J., & Gupta, R. (2010). Evaluating the impact of thermal and pressure treatment in preserving textural quality of selected foods. LWT - Food Science and Technology, 43(3), 525–534.

Nicholas, R. C., & Pflug, I. J. (1960). Effects of high temperature storage on the quality of fresh cucumber pickles. The Glass Packer. Retrieved from http://drpflug.com/publications/043_Pflug-Effects_of_High_Temp_Storage_Pickles.pdf

Nielsen. (2017). IT'S CLEAR: TRANSPARENCY IS WINNING IN THE U.S. RETAIL MARKET. The Nielsen Company (US), LLC. Retrieved from https://www.nielsen.com/wp-content/uploads/sites/3/2019/04/nielsen-clean-label-report-aug-2017.pdf

Nikdel, S., & MacKellar, D. G. (1993). A Microwave System for Continuous Pasteurization of Orange Juice. Undefined. Retrieved February 2, 2021, from /paper/A-Microwave-System-for-Continuous-Pasteurization-of-Nikdel-MacKellar/4d4321fec8427bcbdfb97115837bea1f4f45e0bd

Nikdel, Seifollah., Chen, C. S., Parish, M. E., MacKellar, D. G., & Friedrich, L. M. (1993). Pasteurization of citrus juice with microwave energy in a continuous-flow unit. Journal of Agricultural and Food Chemistry, 41(11), 2116–2119.

Nikmaram, N., & Rosentrater, K. A. (2019). Overview of Some Recent Advances in Improving Water and Energy Efficiencies in Food Processing Factories. Frontiers in Nutrition, 6. Retrieved March 6, 2022, from https://www.frontiersin.org/article/10.3389/fnut.2019.00020

Niu, H., Yuan, L., Zhou, H., Yun, Y., Li, J., Tian, J., Zhong, K., et al. (2022). Comparison of the Effects of High Pressure Processing, Pasteurization and High Temperature Short Time on the Physicochemical Attributes, Nutritional Quality, Aroma Profile and Sensory Characteristics of Passion Fruit Purée. Foods, 11(5), 632. Multidisciplinary Digital Publishing Institute.

Noma, S., Shimoda, M., & Hayakawa, I. (2002). Inactivation of Vegetative Bacteria by Rapid Decompression Treatment. Journal of Food Science, 67(9), 3408–3411.

Oey, I., Lille, M., Loey, A. V., & Hendrickx, M. (2008). Effect of high-pressure processing on colour, texture and flavour of fruit- and vegetable-based food products: A review. Trends in Food Science & Technology, 19(6), 320–328.

Oh, S., & Moon, M.-J. (2003). Inactivation of Bacillus cereus Spores by High Hydrostatic Pressure at Different Temperatures. Journal of Food Protection, 66(4), 599–603.

de Oliveira do Nascimento, K., do Nascimento Dias Paes, S., & Augusta, I. M. (2018). A Review "Clean Labeling": Applications of Natural Ingredients in Bakery Products. Journal of Food and Nutrition Research, 6(5), 285–294.

Oliveira, T. L. C. de, Ramos, A. L. S., Ramos, E. M., Piccoli, R. H., & Cristianini, M. (2015). Natural antimicrobials as additional hurdles to preservation of foods by high pressure processing. Trends in Food Science & Technology, 45(1), 60–85.

Osborn, S. (2015). Labelling relating to natural ingredients and additives. In P. Berryman (Ed.), Advances in Food and Beverage Labelling (pp. 207–221). Woodhead Publishing. Retrieved from https://www-sciencedirect-com.prox.lib.ncsu.edu/science/article/pii/B978178242085950012X

Papageorge, L. M., McFeeters, R. F., & Fleming, H. P. (2003). Factors Influencing Texture Retention of Salt-free, Acidified, Red Bell Peppers during Storage. Journal of Agricultural and Food Chemistry, 51(5), 1460–1463.

Pardo, G., & Zufía, J. (2012). Life cycle assessment of food-preservation technologies. Journal of Cleaner Production, Working towards a more sustainable agri-food industry: Main findings from the Food LCA 2010 conference in Bari, Italy, 28, 198–207.

Park, S. Y., Ha, J.-H., Kim, S. H., & Ha, S.-D. (2017). Effects of high hydrostatic pressure on the inactivation of norovirus and quality of cabbage Kimchi. Food Control, 81, 40–45.

Patange, A., Lu, P., Boehm, D., Cullen, P. J., & Bourke, P. (2019). Efficacy of cold plasma functionalised water for improving microbiological safety of fresh produce and wash water recycling. Food Microbiology, 84, 103226.

Patras, A., Brunton, N. P., Da Pieve, S., & Butler, F. (2009). Impact of high pressure processing on total antioxidant activity, phenolic, ascorbic acid, anthocyanin content and colour of strawberry and blackberry purées. Innovative Food Science & Emerging Technologies, 10(3), 308–313.

Peñas, E., Frias, J., Gomez, R., & Vidal-Valverde, C. (2010). High hydrostatic pressure can improve the microbial quality of sauerkraut during storage. Food Control, 21(4), 524–528.

Peng, J. (2014). Quality evaluation of vegetables processed by microwave sterilization/pasteurization (Ph.D.). Washington State University, Washington, United States. Retrieved February 28, 2022, from https://www.proquest.com/docview/1561147611/abstract/12490EC739FE48E5PQ/1

Pereira, R. N., & Vicente, A. A. (2010). Environmental impact of novel thermal and non-thermal technologies in food processing. Food Research International, 43(7), 1936–1943.

Péréz-Diáz, I., Breidt, F., Buescher, R. W., Arroyo-Lo´pez, F. N., Jime´nez-Dı´az, R., Ferna´ndez, A. G., Gallego, J. B., et al. (2013). Fermented and Acidified Vegetables. In F. P. Downes & K. Ito (Eds.), Compendium of Methods for the Microbiological Examination of Foods (Fifth edition.). Washington, DC: APHA Press. Retrieved from https://ajph.aphapublications.org/doi/10.2105/MBEF.0222.056

Pérez-Díaz, I. m., Kelling, R. e., Hale, S., Breidt, F., & McFeeters, R. f. (2007). Lactobacilli and Tartrazine as Causative Agents of Red-Color Spoilage in Cucumber Pickle Products. Journal of Food Science, 72(7), M240–M245.

Péréz-Diáz, I. M., McFeeters, R. F., Moeller, L., Johanningsmeier, S. D., Hayes, J., Fornea, D. S., Rosenberg, L., et al. (2015). Commercial Scale Cucumber Fermentations Brined with Calcium Chloride Instead of Sodium Chloride. Journal of Food Science, 80(12), M2827–M2836.

Personal communication. (2020, September 14). Proportion of harvested produce processed into fresh-pack pickles.

Pickle Packers International. (2020). A Peck Of Perfectly Plausible Pickle And Pickled Pepper Facts. Ilovepickles.org. Industry Asssociation, . Retrieved from https://www.ilovepickles.org/pickle-facts/crazy-facts/a-peck-of-perfectly-plausible-pickle-and-pickled-pepper-facts/

Plaza, L., Muñoz, M., Ancos, B. D., & Cano, M. P. (2003). Effect of combined treatments of high-pressure, citric acid and sodium chloride on quality parameters of tomato puree. European Food Research and Technology, 216, 514–519.

Polydera, A. C., Stoforos, N. G., & Taoukis, P. S. (2003). Comparative shelf life study and vitamin C loss kinetics in pasteurised and high pressure processed reconstituted orange juice. Journal of Food Engineering, 60(1), 21–29.

Pomerleau, J., Lock, K., Knai, C., & McKee, M. (2005). Interventions Designed to Increase

Adult Fruit and Vegetable Intake Can Be Effective: A Systematic Review of the Literature. *The*

Journal of Nutrition, *135*(10), 2486–2495.

Préstamo, G., Arabas, J., Fonberg-Broczek, M., & Arroyo, G. (2001). Reaction of B. cereus bacteria and peroxidase enzymes under pressures >400 MPa. Journal of Agricultural and Food Chemistry, 49(6), 2830–2834.

Préstamo, G., Palomares, L., & Sanz, P. (2004). Broccoli (Brasica oleracea) treated under pressure-shift freezing process. European Food Research and Technology, 219, 598–604.

Raaholt, B., Isaksson, S., & Hamberg, L. (2013). A tubular microwave sterilisation or pasteurisation process for pumpable foods.

Raaholt, B. W. (2020). Influence of food geometry and dielectric properties on heating performance. In M. Lorence, P. Pesheck, & U. Erle (Eds.), Development of Packaging and Products for Use in Microwave Ovens (pp. 74–93). Woodhead Publishing.

Raaholt, B. W., Isaksson, S., Hamberg, L., Fhager, A., & Hamnerius, Y. (2016). Continuous tubular microwave heating of homogeneous foods: Evaluation of heating uniformity. Journal of Microwave Power and Electromagnetic Energy, 50(1), 43–65. Taylor & Francis.

Raghavan, V., Orsat, V., & Meda, V. (2005). The Microwave Processing of Foods. Stewart Postharvest Review, 1, 1–8.

Ramaswamy, H. S., Shao, Y., Bussey, J., & Austin, J. (2013). Screening of twelve Clostridium botulinum (group I) spores for high-pressure resistance at elevated-temperatures. Food and Bioproducts Processing, 91(4), 403–412.

Ramaswamy, Hosahalli S., & Shao, Y. (2010). High Pressure Destruction Kinetics of Clostridium Sporogenes Spores in Salmon Slurry at Elevated Temperatures. International Journal of Food Properties, 13(5), 1074–1091.

Rasanayagam, V., Balasubramaniam, V. M., Ting, E., Sizer, C. E., Bush, C., & Anderson, C. (2003). Compression Heating of Selected Fatty Food Materials during High-pressure Processing. Journal of Food Science, 68(1), 254–259.

Rastogi, N. K., Raghavarao, K. S. M. S., Balasubramaniam, V. M., Niranjan, K., & Knorr, D. (2007). Opportunities and Challenges in High Pressure Processing of Foods. Critical reviews in food science and nutrition, 47(1), 69–112.

Reddy, N. R., Solomon, H. M., Fingerhut, G. A., Rhodehamel, E. J., Balasubramaniam, V. M., & Palaniappan, S. (1999). Inactivation of Clostridium Botulinum Type E Spores by High Pressure Processing. Journal of Food Safety, 19(4), 277–288.

Reineke, K., Mathys, A., & Knorr, D. (2011). The Impact of High Pressure and Temperature on Bacterial Spores: Inactivation Mechanisms of Bacillus subtilis above 500 MPa. Journal of Food Science, 76(3), M189–M197.

Richter, T., Sterr, J., Jost, V., & Langowski, H.-C. (2010). High pressure-induced structural effects in plastic packaging. High Pressure Research, 30(4), 555–566.

Ritz, M., Freulet, M., Orange, N., & Federighi, M. (2000). Effects of high hydrostatic pressure on membrane proteins of Salmonella typhimurium. International Journal of Food Microbiology, 55(1), 115–119.

Robertson, R. E., Carroll, T., & Pearce, L. E. (2008). Bacillus Spore Inactivation Differences after Combined Mild Temperature and High Pressure Processing Using Two Pressurizing Fluids. Journal of Food Protection, 71(6), 1186–1192.

Rodrigo, C., Rodrigo, M., Fiszman, S., & Sanchez, T. (1997). Thermal Degradation of Green Asparagus Texture. Journal of food protection, 60(3), 315–320.

Rodriguez-Gonzalez, O., Buckow, R., Koutchma, T., & Balasubramaniam, V. M. (2015). Energy Requirements for Alternative Food Processing Technologies—Principles, Assumptions, and Evaluation of Efficiency. Comprehensive Reviews in Food Science and Food Safety, 14(5), 536–554.

Rolle, R. S. (2006). Processing of Fruits and Vegetables for Reducing Postharvest Losses and Adding Value. In R. S. Rolle (Ed.), Postharvest Management of Fruit and Vegetables in the Asia-Pacific Region (pp. 32–42). Tokyo

Sabliov, C., & Boldor, D. (2011). Instrumentation, control, and modeling of continuous flow microwave processing. Thermal processing of foods: Control and automation, 165–194. Wiley-Blackwell.

Sachdeva, S., Sachdev, T. R., & Sachdeva, R. (2013). Increasing Fruit and Vegetable Consumption: Challenges and Opportunities. Indian Journal of Community Medicine: Official Publication of Indian Association of Preventive & Social Medicine, 38(4), 192–197.

Salazar-González, C., San Martín-González, M. F., López-Malo, A., & Sosa-Morales, M. E. (2012). Recent Studies Related to Microwave Processing of Fluid Foods. Food and Bioprocess Technology, 5(1), 31–46.

Saldana, G., & Meyer, R. (2006). Effects of Added Calcium on Texture and Quality of Canned Jalapeno Peppers. Journal of Food Science, 46, 1518–1520.

Saltveit, M. E., & McFeeters, R. F. (1980). Polygalacturonase Activity and Ethylene Synthesis during Cucumber Fruit Development and Maturation 1. Plant Physiology, 66(6), 1019–1023.

Salvi, D., Ortego, J., Arauz, C., Sabliov, C. M., & Boldor, D. (2009). Experimental study of the effect of dielectric and physical properties on temperature distribution in fluids during continuous flow microwave heating. Journal of Food Engineering, 93(2), 149–157.

Sampedro, F., McAloon, A., Yee, W., Fan, X., & Geveke, D. J. (2014). Cost Analysis and Environmental Impact of Pulsed Electric Fields and High Pressure Processing in Comparison with Thermal Pasteurization. Food and Bioprocess Technology, 7(7), 1928–1937.

Sánchez-Moreno, C., Plaza, L., Elez-Martínez, P., Ancos, B. D., Martín-Belloso, O., & Cano, M. P. (2005). Impact of High Pressure and Pulsed Electric Fields on Bioactive Compounds and

Antioxidant Activity of Orange Juice in Comparison with Traditional Thermal Processing. Journal of Agricultural and Food Chemistry, 53(11), 4403–4409.

Sancho, F., Lambert, Y., Demazeau, G., Largeteau, A., Bouvier, J. M., & Narbonne, J. F. (1999). Effect of ultra-high hydrostatic pressure on hydrosoluble vitamins. Journal of Food engineering., 39(3), 247–253.

Sandeep, K., & Puri, V. (2001). Aseptic processing of liquid and particulate foods. Food Processing Operations Modeling: Design and Analysis (pp. 13–52). Florida: CRC Press.

Scott-Thomas, C. (2013, June). What do 'natural' and 'clean label' mean anyway? Food Navigator. Retrieved from https://www.foodnavigator.com/Article/2013/06/18/What-do-natural-and-clean-label-mean-anyway

Sereno, A. M. (2000). Thermal Properties and State Diagrams of Fruits and Vegetables by DSC. In J. E. Lozano, C. Anon, G. V. Barbosa-Canovas, & E. Parada-Arias (Eds.), Trends in Food Engineering, Food Preservation Technology Series (pp. 77–88). Pennsylvania: CRC Press.

Shahidi, F. (2000). Antioxidants in food and food antioxidants. Food / Nahrung, 44(3), 158–163.

Shoup, M. E. (2019). Nielsen: How do sales of sustainable products stack up? (Vol. 2020). Retrieved from https://www.foodnavigator-usa.com/Article/2018/10/24/Nielsen-How-do-sales-of-sustainable-products-stack-up

Simunovic, J. (2017, July 13). Modular devices and systems for continuous flow thermal processing using microwaves. Retrieved February 16, 2021, from https://patents.google.com/patent/US20170196244A1/en

Simunovic, J., & DROZD, J. M. (2012, December 25). Method for processing biomaterials. Retrieved February 16, 2021, from https://patents.google.com/patent/US8337920B2/en

Simunovic, J., & Sandeep, K. P. (2022). 8—Key technological advances and industrialization of continuous flow microwave processing for foods and beverages. In P. Juliano, R. Buckow, M. H. Nguyen, K. Knoerzer, & J. Sellahewa (Eds.), Food Engineering Innovations Across the Food Supply Chain (pp. 149–162). Academic Press. Retrieved February 28, 2022, from https://www.sciencedirect.com/science/article/pii/B9780128212929000121

Simunovic, J., Swartzel, K. R., Truong, V.-D., Cartwright, G., Coronel, P., Sandeep, K. P., & Parrott, D. (2014, June 3). Methods and apparatuses for thermal treatment of foods and other biomaterials, and products obtained thereby. Retrieved February 16, 2021, from https://patents.google.com/patent/US8742305B2/en

Simunovic, J., Swartzel, K. R., Truong, V.-D., Cartwright, G. D., Sandeep, K. P., Parrott, D. L., & Coronel, P. (2017, April 11). Methods and apparatuses for thermal treatment of foods and other biomaterials, and products obtained thereby. Retrieved January 29, 2021, from https://patents.google.com/patent/US9615593B2/en?inventor=Josip+Simunovic

Sipahioglu, O., Barringer, S. A., Taub, I., & Prakash, A. (2003). Modeling the Dielectric Properties of Ham as a Function of Temperature and Composition. Journal of Food Science, 68(3), 904–909.

Sohn, K.-H., & Lee, H.-J. (2002). Effects of high pressure treatment on the quality and storage of kimchi. International Journal of Food Science & Technology, 33(4), 359–365.

Stanley, R. A., & Petersen, K. (2017). Microwave-assisted pasteurization and sterilization—Commercial perspective. The Microwave Processing of Foods (Second Edition., pp. 200–219). Elsevier Ltd. Retrieved from http://dx.doi.org/10.1016/B978-0-08-100528-6.00010-3

Steed, L. E., Truong, V.-D., Simunovic, J., Sandeep, K. P., Kumar, P., Cartwright, G. D., & Swartzel, K. R. (2008). Continuous Flow Microwave-Assisted Processing and Aseptic Packaging of Purple-Fleshed Sweetpotato Purees. Journal of Food Science, 73(9), E455–E462.

Straits Research. (2019, May). Pickles Market: Information by Type (Fruit, Vegetable), Taste (Sweet, Salty), Distribution Channel (Supermarkets & Hypermarkets, Convenience Stores) and Regional Outlook—Forecast Till 2026. Straits Research. Market research, . Retrieved from https://straitsresearch.com/report/pickles-market

Stratakos, A. C., Delgado-Pando, G., Linton, M., Patterson, M. F., & Koidis, A. (2016). Industrial scale microwave processing of tomato juice using a novel continuous microwave system. Food Chemistry, 190, 622–628.

Sun, E., Datta, A., & Lobo, S. (1995). Composition-Based Prediction of Dielectric Properties of Foods. Journal of Microwave Power and Electromagnetic Energy, 30(4), 205–212. Taylor & Francis.

Swain, M. R., Anandharaj, M., Ray, R. C., & Rani, R. P. (2014). Fermented Fruits and Vegetables of Asia: A Potential Source of Probiotics. Biotechnology Research International, 2014. Retrieved from https://www.hindawi.com/journals/btri/2014/250424/

Sweetman, J. (2016). Commercialization of foods for customers with specific dietary needs. In Steve Osborn & W. Morley (Eds.), Developing Food Products for Consumers with Specific Dietary Needs (pp. 63–77). Woodhead Publishing. Retrieved from https://doi.org/10.1016/B978-0-08-100329-9.00004-9

Tamer, C. E. (2012). Quality evaluation of canned cauliflower pickles prepared with different ingredients. African Journal of Agricultural Research, 7(10), 1550–1555.

Tan, C. P., Che Man, Y. B., Jinap, S., & Yusoff, M. S. A. (2001). Effects of microwave heating on changes in chemical and thermal properties of vegetable oils. Journal of the American Oil Chemists' Society, 78(12), 1227–1232.

Tang, J. (2015). Unlocking Potentials of Microwaves for Food Safety and Quality. Journal of Food Science, 80(8), E1776–E1793.

Tang, J., Hong, Y.-K., Inanoglu, S., & Liu, F. (2018). Microwave pasteurization for ready-to-eat meals. Current Opinion in Food Science, Food Engineering & Processing part 1 * Food Engineering & Processing part 2 * Food Mycology, 23, 133–141.

Tang, J., Liu, F., Pathak, S. K., & Eves, E. E. I. (2005, March 17). Apparatus and method for heating objects with microwaves. Retrieved January 29, 2021, from https://patents.google.com/patent/WO2005023013A2/en

Tang, Z., Mikhaylenko, G., Liu, F., Mah, J.-H., Pandit, R., Younce, F., & Tang, J. (2008). Microwave sterilization of sliced beef in gravy in 7-oz trays. Journal of Food Engineering, 89(4), 375–383.

Terefe, N. S., Buckow, R., & Versteeg, C. (2014). Quality-Related Enzymes in Fruit and Vegetable Products: Effects of Novel Food Processing Technologies, Part 1: High-Pressure Processing. Critical Reviews in Food Science and Nutrition, 54(1), 24–63.

Teseme, W. B., & Weldeselassie, H. W. (2020). Review on the Study of Dielectric Properties of Food Materials. American Journal of Engineering and Technology Management, 5(5), 76.

Thakur, B. R., & Nelson, P. E. (1998). High-pressure processing and preservation of food. Food Reviews International, 14(4), 427–447.

Tholozan, J. L., Ritz, M., Jugiau, F., Federighi, M., & Tissier, J. P. (2000). Physiological effects of high hydrostatic pressure treatments on Listeria monocytogenes and Salmonella typhimurium. Journal of Applied Microbiology, 88(2), 202–212.

Tian, J., Chen, J., Lv, F., Chen, S., Chen, J., Liu, D., & Ye, X. (2016). Domestic cooking methods affect the phytochemical composition and antioxidant activity of purple-fleshed potatoes. Food Chemistry, 197, 1264–1270.

Tinello, F., & Lante, A. (2018). Recent advances in controlling polyphenol oxidase activity of fruit and vegetable products. Innovative Food Science & Emerging Technologies, 50, 73–83.

Tola, Yetenayet B., & Ramaswamy, H. S. (2018). Novel processing methods: Updates on acidified vegetables thermal processing. Current Opinion in Food Science, 23, 64–69.

Tola, Yetenayet Bekele, & Ramaswamy, H. S. (2013). Evaluation of high pressure (HP) treatment for rapid and uniform pH reduction in carrots. Journal of Food Engineering, 116(4), 900–909.

Tola, Yetenayet Bekele, & Ramaswamy, H. S. (2014). Combined effects of high pressure, moderate heat and pH on the inactivation kinetics of Bacillus licheniformis spores in carrot juice. Food Research International, 62, 50–58.

Tribst, A. A. L., Leite Júnior, B. R. de C., de Oliveira, M. M., & Cristianini, M. (2016). High pressure processing of cocoyam, Peruvian carrot and sweet potato: Effect on oxidative enzymes and impact in the tuber color. Innovative Food Science & Emerging Technologies, 34, 302–309.

USDA. (2019). United States Standards for Grades of Pickles (84 FR 16381.).

USDA. (2020). Vegetables 2019 Summary. USDA, National Agricultural Statistics Service.

Vadivambal, R., & Jayas, D. (2008). Non-uniform Temperature Distribution During Microwave Heating of Food Materials—A Review. Food and Bioprocess Technology, 3, 161–171.

Valero, M., & Giner, M. J. (2006). Effects of antimicrobial components of essential oils on growth of Bacillus cereus INRA L2104 in and the sensory qualities of carrot broth. International Journal of Food Microbiology, 106(1), 90–94.

Venkatesh, M. S., & Raghavan, G. S. V. (2004). An Overview of Microwave Processing and Dielectric Properties of Agri-food Materials. Biosystems Engineering, 88(1), 1–18.

Venkatesh, M. S., & Raghavan, V. (2005). An Overview of Dielectric Properties Measuring Techniques. Canadian Biosystems Engineering / Le Genie des biosystems au Canada, 47, 15–30.

Vierhile, T. (2016). Clean Label Focus: What are Consumers Saying and What is the Industry Doing? Clean label conference 2016. Canadean.

Wang, D., Ma, Y., Sun, X., Zhang, M., Zhao, Y., & Zhao, X. (2019). Effect of dense phase carbon dioxide treatment on physicochemical and textural properties of pickled carrot. CyTA - Journal of Food, 17(1), 988–996.

Wang, Y., Tang, J., Rasco, B., Kong, F., & Wang, S. (2008). Dielectric properties of salmon fillets as a function of temperature and composition. Journal of Food Engineering, 87(2), 236–246.

Watrous, M. (2015). Noodles & Co. Announces clean label commitment. Food Business News. Retrieved January 29, 2022, from https://www.foodbusinessnews.net/articles/6090-noodles-co-announces-clean-label-commitment

Weemaes, C. A., Cordt, S. V. D., Ludikhuyze, L. R., Broeck, I. V. den, Hendrickx, M. E., & Tobback, P. P. (1997). Influence of pH, benzoic acid, EDTA, and glutathione on the pressure and/or temperature inactivation kinetics of mushroom polyphenoloxidase. Biotechnology Progress, 13(1), 25–32.

Wei, C.-I., Cook, D. L., & Kirk, J. R. (1985). Use of chlorine compounds in the food industry. Food technology. Retrieved February 25, 2022, from https://scholar.google.com/scholar_lookup?title=Use+of+chlorine+compounds+in+the+food+industry&author=Wei%2C+Cheng-I.&publication_year=1985

Williams, L. A. (2019). Mindful Consumers Drive Clean Label Momentum. Food Technology, 73(3). Retrieved from https://www.ift.org/news-and-publications/food-technology-magazine/issues/2019/march/features/new-organic-natural-non-gmo-product-introductions

Wray, D., & Ramaswamy, H. S. (2015). Novel Concepts in Microwave Drying of Foods. Drying Technology, 33(7), 769–783. Taylor & Francis.

Wu, W., Xiao, G., Yu, Y., Xu, Y., Wu, J., Peng, J., & Li, L. (2021). Effects of high pressure and thermal processing on quality properties and volatile compounds of pineapple fruit juice. Food Control, 130, 108293.

Xu, F., Zheng, Y., Yang, Z., Cao, S., Shao, X., & Wang, H. (2014). Domestic cooking methods affect the nutritional quality of red cabbage. Food Chemistry, 161, 162–167.

Yang, H. W., & Gunasekaran, S. (2004). Comparison of temperature distribution in model food cylinders based on Maxwell's equations and Lambert's law during pulsed microwave heating. Journal of Food Engineering, 64(4), 445–453.

Yavuz, N., Foster, L., Sharma, T., Patel, K., Stoforos, G., Sandeep, K., Palnitkar, P., et al. (2018). Hot-fill Pasteurization of Cucumber Pickle Spears: An Alternative to Tunnel Pasteurization. Food Protection Trends, 38(4). Retrieved from researchgate.net/publication/326466066_Hot-fill_Pasteurization_of_Cucumber_Pickle_Spears_An_Alternative_to_Tunnel_Pasteurization

Yi, J., Kebede, B. T., Grauwet, T., Van Loey, A., Hu, X., & Hendrickx, M. (2016). Comparing the Impact of High-Pressure Processing and Thermal Processing on Quality of "Hayward" and "Jintao" Kiwifruit Purée: Untargeted Headspace Fingerprinting and Targeted Approaches. Food and Bioprocess Technology, 9(12), 2059–2069.

Yildiz, S., Pokhrel, P. R., Unluturk, S., & Barbosa-Cánovas, G. V. (2021). Shelf life extension of strawberry juice by equivalent ultrasound, high pressure, and pulsed electric fields processes. Food Research International, 140, 110040.

Yoo, S., Sigua, G., Min, D., & Pascall, M. A. (2014). The Influence of High-pressure Processing on the Migration of Irganox 1076 from Polyethylene Films. Packaging Technology and Science, 27(4), 255–263.

Zhang, H., Bhunia, K., Munoz, N., Li, L., Dolgovskij, M., Rasco, B., Tang, J., et al. (2017). Linking morphology changes to barrier properties of polymeric packaging for microwave-assisted thermal sterilized food. Journal of Applied Polymer Science, 134(44), 45481.

Zhang, H., Bhunia, K., Tang, J., & Sablani, S. (2018). Packaging technology for microwave sterilization. Packaging for Nonthermal Processing of Food, 205–223.

Zhang, H. Q., Barbosa-Cánovas, G. V., Balasubramaniam, V. M. B., Dunne, C. P., Farkas, D. F., & Yuan, J. T. C. (2011). Nonthermal Processing Technologies for Food. John Wiley & Sons.

Zhang, Y., Yang, H., Yan, B., Zhu, H., Gao, W., Zhao, J., Zhang, H., et al. (2021). Continuous flow microwave system with helical tubes for liquid food heating. Journal of Food Engineering, 294, 110409.

Zou, Y., & Jiang, A. (2016). Effect of ultrasound treatment on quality and microbial load of carrot juice. Food Science and Technology, 36, 111–115. Sociedade Brasileira de Ciência e Tecnologia de Alimentos.

CHAPTER 2: INTRODUCTION

2.1. BACKGROUND

Acidified peppers, including jalapeno, banana, and red bell peppers are popular ingredients in pizzas, sandwiches, and pastas, used extensively in food service and sold for domestic use to a smaller extent. These are known to undergo softening after heat processing and during storage when produced using current practices (Gu, Howard, & Wagner, 1999b; Lee & Howard, 1999; Papageorge, McFeeters, & Fleming, 2003; Saldana & Meyer, 2006). The industry is urging research efforts in addressing this issue using a clean label approach. As acidified red bell peppers are the most prone to softening (Breidt, 2006; Koskiniemi et al., 2013; Papageorge et al., 2003), these present an ideal candidate for new process development. Continuous flow microwave processing technology has demonstrated potential in yielding high quality and safe vegetable products, which have received a no-objection from FDA and been commercialized. Processing using microwaves also offers advantages in increases process efficiency such as reduced processing times and simple start-up and shut-down, as well as in environmental sustainability including reduced water consumption, global warming potential and cumulative energy demand (Pardo & Zufía, 2012).

Processing parameters can have an influence on the safety, quality, and overall sensory characteristics, ultimately affecting consumer acceptability. The primary target of any new process is to ensure that the product is safe for human consumption. For pickled vegetables produced by acidification, the required F value is 1.2 min at T_{ref} of 71.1°C and z value of 10.5°C for the 5-log inactivation of *E.coli* O157:H7 (Breidt, Sandeep, & Arritt, 2010), which is the organism of concern in products with pH > 3.3 and ≤ 4.1 (Breidt et al., 2007). However, when pH was 4.1-4.6, the organism of concern was found to be *Listeria monocytogenes*. A 5-log

inactivation process required an F value of 5.6 min at T_{ref} of 71.1°C and z value of 9.3°C (Breidt et al., 2014). When developing a new process, it is important to study its effects on the sensory properties, which is the most important driver for purchase and consumer satisfaction (Imtiyaz, Soni, & Yukongdi, 2021).

Sensorially, the goal of the industry is to retain fresh-like characteristics of peppers after processing and during the entire shelf life. To evaluate and guide process design, a framework for determining sensory quality is necessary. Descriptive analysis (DA) using a trained panel is a powerful tool to obtain the complete sensory profile of the samples and identify deviations in various sensory attributes in a detailed manner. The rationale is that, when differences are not identified by a trained sensory panel, it would most likely not be recognizable to an untrained consumer panel, since a trained panel will have a higher sensitivity than a consumer panel (Lawless & Heymann, 2010). Quantitative DA provides complete information on the perceived sensory attributes and their intensities. In general, recruitment of a panel for DA begins with screening panelists for availability, health, general awareness on product attributes, sensory acuity and rating ability (Munoz & Civille, 1992). This is followed by training of the panel and development of a lexicon that will be used as a common vocabulary for the panelists to describe and evaluate products. A sensory lexicon is a standardized set of words also known as descriptors or attributes, that are used to describe various sensory characteristics of a food product. Lexicons are useful communication tools between multiple stakeholders such as marketing, research and development, suppliers, manufacturing, etc. that are involved in the business (Lawless & Civille, 2013). The lexicon development process starts with presenting a wide range of representative samples of the target product category, which are evaluated by the panelists who generate words or attributes to describe the samples. For example, as many as 78

unique samples were evaluated to fully describe the various flavor and texture differences that characterize apples (Bowen, Blake, Tureček, & Amyotte, 2019). The panel defines each of the attributes generated and develops procedures to evaluate them consistently. Further understanding of definitions is facilitated by selecting references for each of the attributes and assigning scores to those references to anchor the response scale. Finally, the developed lexicon is reviewed for completeness of defined terms, extent of coverage, non-redundancy, and use of objective, non-hedonic and singular terms (Suwonsichon, 2019). Depending on the product and the diversity that exists in the product category, a panel may generate few to several attributes which varies with the kind of product being studied (Chambers IV, Lee, Chun, & Miller, 2012; Guzmán & Bosland, 2017; Hongsoongnern & Chambers, 2008; Koppel & Chambers, 2010; Talavera-Bianchi, Chambers IV, & Chambers, 2010). Sensory wheels are often used as teaching tools for the panel to build perspective on the various attributes and the relationships among them (Lawless, Hottenstein, & Ellingsworth, 2012). The time taken for training could range between 10 h (Moskowitz, 2018) up to 120 h (Suwonsichon, Chambers IV, Kongpensook, & Oupadissakoon, 2012) depending on the complexity of the product.

Sensory attributes such as sweetness, sourness, saltiness, spiciness, dill, vinegar, astringency, bitterness, overall intensity, other/off-flavor, crunchiness and firmness were identified and referenced for pickled cucumbers (Johanningsmeier, Thompson, & Fleming, 2003). Another study that characterized the sensory quality of pickled cucumbers directly acidified by verjuice included attributes such as appearance (green color, brightness), orthonasal odor (vinegar, cucumber smell), taste (acidity, sweetness, salt, bitterness), retronasal odor (cucumber, vinegar, cooked vegetable aromas), tactile sensation (crunchiness, firmness, and astringency), and trigeminal pungency (Matos et al., 2019). Texture attributes such as hardness

and brittleness were found to be important indicators of sensory quality of pickled carrots. These were related to the cell structure parameters such as the pectin type and content that changed with the processing method (Llorca et al., 2001; Wang et al., 2019). In the case of raw, sous-vide and cooked carrots processed by HPP, the appearance (intensity of orange, visual firmness, brightness, surface moisture, flexibility), odor (odor impact, green, processed), texture (fibrous, crunchy, moisture in mouth, chewing time), flavor (flavor impact, sweetness, bitterness, processed, green) and aftertaste/ after feel (aftertaste impact, bitterness) were generated as the descriptors (Araya et al., 2009). Pickled beets were characterized for odor (pungent, sour, pickled cucumber, sweet, seasoning, off-odor), taste (sour, pickled cucumber, seasoning, red beet, sweet, fruit, salt, bitter, off-taste, overall quality), color and texture (Kosson, Elkner, & Szafirowska, 2011). Thus, the descriptors change with products, variants, processes, ingredients, etc. and lexicon development is the most critical step in obtaining accurate and repeatable results from DA.

2.2. RESEARCH OBJECTIVES

The overall goal of this work is to fundamentally understand the characteristics of acidified red bell peppers that will help to guide product and process design using microwave technology as a step towards developing clean label pickled vegetables.

1. Study the electrical and thermal properties of acidified red bell peppers including dielectric constant and loss factor, electrical conductivity, and specific heat capacity to guide product and process design.
2. Enable prediction of dielectric properties of acidified red bell peppers based on composition, to facilitate technology transfer and adoption by the industry.

3. Develop a sensory lexicon for fresh and preserved peppers as a quality evaluation tool to guide new process development.

2.3. SIGNIFANCE OF THIS WORK

Conventionally processed acidified peppers undergo softening during storage. To cater to the growing clean label demand, exploring the feasibility of advanced processing technologies to achieve improved quality has become necessary. This work attempts to lay the foundation for new process development using continuous flow microwave technology, which has demonstrated capabilities in quality improvement and commercialization of vegetable products in the clean label way.

REFERENCES

Anthon, G. E., Sekine, Y., Watanabe, N., & Barrett, D. M. (2002). Thermal Inactivation of Pectin Methylesterase, Polygalacturonase, and Peroxidase in Tomato Juice. *Journal of Agricultural and Food Chemistry*, *50*(21), 6153–6159. American Chemical Society.

Bowen, A. J., Blake, A., Tureček, J., & Amyotte, B. (2019). External preference mapping: A guide for a consumer-driven approach to apple breeding. *Journal of Sensory Studies*, *34*(1), e12472.

Breidt, F. J. (2006). Safety of minimally processed, acidified and fermented vegetable products. In G. M. Sapers, J. R. Gorny, & A. E. Yousef (Eds.), *Microbiology of Fruits and Vegetables* (pp. 313–335). Boca Raton: CRC Press. Retrieved from https://www.ars.usda.gov/ARSUserFiles/60701000/FoodSafetyPublications/p337.pdf

Breidt, Fred, Hayes, J., & McFeeters, R. F. (2007). Determination of 5-Log Reduction Times for Food Pathogens in Acidified Cucumbers during Storage at 10 and 25°C. *Journal of Food Protection*, *70*(11), 2638–2641.

Breidt, Frederick, Kay, K., Osborne, J., Ingham, B., & Arritt, F. (2014). Thermal Processing of Acidified Foods with pH 4.1 to pH 4.6. *Food Protection Trends*, *34*(2), 132–138. Des Moines, United Kingdom: Allen Press Inc.

Breidt, Frederick, Sandeep, K. P., & Arritt, F. M. (2010). Use of Linear Models for Thermal Processing of Acidified Foods. *Food Protection Trends*, *30*(5), 268–272. Des Moines, United Kingdom: Allen Press Inc.

Chambers IV, E., Lee, J., Chun, S., & Miller, A. E. (2012). Development of a Lexicon for Commercially Available Cabbage (Baechu) Kimchi. *Journal of Sensory Studies*, *27*(6), 511–518.

Cho, M. J., & Buescher, R. W. (2012). Potential Role of Native Pickling Cucumber Polygalacturonase in Softening of Fresh Pack Pickles. *Journal of Food Science*, *77*(4), C443–C447.

Gu, Y. S., Howard, L. R., & Wagner, A. B. (1999). Physicochemical Factors Affecting Firmness of Pasteurized Jalapeno Pepper Rings. *Journal of Food Quality*, *22*(6), 619–629.

Guzmán, I., & Bosland, P. W. (2017). Sensory properties of chile pepper heat – and its importance to food quality and cultural preference. *Appetite*, *117*, 186–190.

Hongsoongnern, P., & Chambers, E. (2008). A Lexicon for Texture and Flavor Characteristics of Fresh and Processed Tomatoes. *Journal of Sensory Studies*, *23*(5), 583–599.

Imtiyaz, H., Soni, P., & Yukongdi, V. (2021). Role of Sensory Appeal, Nutritional Quality, Safety, and Health Determinants on Convenience Food Choice in an Academic Environment. *Foods (Basel, Switzerland)*, *10*(2), 345.

Jen, J. J., & Robinson, M. L. (1984). Pectolytic Enzymes in Sweet Bell Peppers (Capsicum annuum L.). *Journal of Food Science*, *49*(4), 1085–1087.

Johanningsmeier, S., Thompson, R. L., & Fleming, H. (2003). Bag-in-box technology: Sensory quality of pickles produced from process-ready, fermented cucumbers. *Pickle Pak Sci*, *8*.

Koppel, K., & Chambers, E. (2010). Development and application of a lexicon to describe the flavor of pomegranate juice. *Journal of Sensory Studies*, *25*(6), 819–837.

Koskiniemi, C. B., Truong, V.-D., McFeeters, R. F., & Simunovic, J. (2013). Quality evaluation of packaged acidified vegetables subjected to continuous microwave pasteurization. *LWT - Food Science and Technology*, *54*(1), 157–164.

Kosson, R., Elkner, K., & Szafirowska, A. (2011). Quality of Fresh and Processed Red Beet from Organic and Conventional Cultivation. *Vegetable Crops Research Bulletin*, *75*.

Lawless, & Civille, G. V. (2013). Developing Lexicons: A Review. *Journal of Sensory Studies*, *28*(4), 270–281.

Lawless, Hottenstein, A., & Ellingsworth, J. (2012). The mccormick spice wheel: A systematic and visual approach to sensory lexicon development. *Journal of Sensory Studies*, *27*(1), 37–47.

Lee, Y., & Howard, L. (1999). Firmness and Phytochemical Losses in Pasteurized Yellow Banana Peppers (Capsicum annuum) As Affected by Calcium Chloride and Storage. *Journal of Agricultural and Food Chemistry*, *47*(2), 700–703. American Chemical Society.

Llorca, E., Puig, A., Hernando, I., Salvador, A., Fiszman, S. M., & Lluch, M. A. (2001). Effect of fermentation time on texture and microstructure of pickled carrots. *Journal of the Science of Food and Agriculture*, *81*(15), 1553–1560.

Matos, A. D. de, Marangon, M., Magli, M., Cianciabella, M., Predieri, S., Curioni, A., & Vincenzi, S. (2019). Sensory characterization of cucumbers pickled with verjuice as novel acidifying agent. *Food Chemistry*, *286*.

Moskowitz, H. R. (2018). *Applied Sensory Analysis of Foods*. Routledge.

Munoz, A. M., & Civille, G. V. (1992). The Spectrum Descriptive Analysis Method. In R. Hootman (Ed.), *ASTM Manual on descriptive sensory analysis for sensory evaluation*, ASTM Manual Series (pp. 22–34). Baltimore, MD: ASTM.

Ogasawara, S., Abe, K., & Nakajima, T. (2007). Pepper β-Galactosidase 1 (PBG1) Plays a Significant Role in Fruit Ripening in Bell Pepper (Capsicum annuum). *Bioscience, Biotechnology, and Biochemistry*, *71*(2), 309–322.

Papageorge, L. M., McFeeters, R. F., & Fleming, H. P. (2003). Factors Influencing Texture Retention of Salt-free, Acidified, Red Bell Peppers during Storage. *Journal of Agricultural and Food Chemistry*, *51*(5), 1460–1463.

Pardo, G., & Zufía, J. (2012). Life cycle assessment of food-preservation technologies. Journal of Cleaner Production, Working towards a more sustainable agri-food industry: Main findings from the Food LCA 2010 conference in Bari, Italy, 28, 198–207.

Prabha, T. N., Neelwarne, B., & Tharanathan, R. N. (1998). Carbohydrate changes in ripening Capsicum annuum in relation to textural degradation. *Zeitschrift für Lebensmitteluntersuchung und -Forschung A, 206*(2), 121–125.

Pressey, R., & Avants, J. K. (1973). Two forms of polygalacturonase in tomatoes. *Biochimica et Biophysica Acta (BBA)—Enzymology*, *309*(2), 363–369.

Rao, T. V. R., Gol, N. B., & Shah, K. K. (2011). Effect of postharvest treatments and storage temperatures on the quality and shelf life of sweet pepper (Capsicum annum L.). *Scientia Horticulturae*, *132*, 18–26.

Saldana, G., & Meyer, R. (2006). Effects of Added Calcium on Texture and Quality of Canned Jalapeno Peppers. *Journal of Food Science*, *46*, 1518–1520.

Sethu, P., Prabha, T. N., & Tharanathan, R. N. (1996). Post-harvest biochemical changes associated with the softening phenomenon in Capsicum annuum fruits. *Phytochemistry*, *42*(4), 961–966.

Suwonsichon, S., Iv, E. C., Kongpensook, V., & Oupadissakoon, C. (2012). Sensory lexicon for mango as affected by cultivars and stages of ripeness. *Journal of Sensory Studies*, *27*(3), 148–160.

Suwonsichon, Suntaree. (2019). The Importance of Sensory Lexicons for Research and Development of Food Products. *Foods*, *8*(1). Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6352027/

Talavera-Bianchi, M., Chambers IV, E., & Chambers, D. H. (2010). Lexicon to describe flavor of fresh leafy vegetables. *Journal of Sensory Studies*, *25*(2), 163–183.

Araya, X. I. T, Smale, N., Zabaras, D., Winley, E., Forde, C., Stewart, C. M., & Mawson, A. J. (2009). Sensory perception and quality attributes of high pressure processed carrots in comparison to raw, sous-vide and cooked carrots. *Innovative Food Science & Emerging Technologies*, *10*(4), 420–433.

Wang, D., Ma, Y., Sun, X., Zhang, M., Zhao, Y., & Zhao, X. (2019). Effect of dense phase carbon dioxide treatment on physicochemical and textural properties of pickled carrot. *CyTA - Journal of Food, 17*(1), 988–99

CHAPTER 3: ELECTRICAL AND THERMAL CHARACTERIZATION OF FRESH AND ACIDIFIED RED BELL PEPPERS TO GUIDE MICROWAVE PROCESS DESIGN

3.1. ABSTRACT

The demand for improved quality and clean label foods is driving the need for using advanced processing technologies such as microwave processing. To develop a process for the manufacture of acidified red bell peppers using microwaves, it is necessary to understand its dielectric and thermal characteristics that influence the heating characteristics. In this study, the loss tangents of 20 different compositions (with 5 different levels of acetic acid and 4 different levels of salt in a full factorial design) of red bell pepper homogenates were determined. Additionally, the effects of composition, temperature, frequency, and electrical conductivity on the loss tangent were modeled to enable prediction of dielectric properties. Loss tangent was found to increase with temperature and salt concentration, which affects the conversion of microwave energy into heat and its penetration depth. As a rule of thumb, the product dimensions are set to be 2 to 2.5 times the depth of penetration. The low loss tangent of fresh red bell peppers could be reasoned by a high specific heat capacity of 2.5982 J/g°C at 20°C. The proportion of transmitted power across all samples regardless of varying composition did not exceed 50%. This prompts that extrinsic factors such as cavity dimensions and its material of construction along with the power supplied by the magnetron need to be given due consideration to reduce much of the reflection of microwave energy. Models to predict loss tangent of red bell pepper homogenates based on known composition and electrical conductivity at temperature and frequency of interest have been proposed with prediction accuracies > 80%. Thus, this work provides fundamental information for designing a microwave process for the development of clean label acidified red bell peppers.

Practical Application

There is limited information on the properties of pickled red bell peppers in general. This work guides product and process design for achieving clean label acidified red bell peppers of improved quality using an efficient manufacturing process.

3.2. INTRODUCTION

Microwaves are part of the electromagnetic spectrum with frequencies ranging from 0.3 GHz to 300 GHz (Datta & Anantheswaran, 2001). By causing dipolar molecules and ions to vibrate under the influence of an alternating electric field, treatment with microwaves leads to volumetric heating of food. The dielectric and thermal properties of food influence its heating characteristics when treated with microwaves. Dielectric properties include dielectric constant (ε'), which relates to the ability of food to store microwave energy, and dielectric loss factor (ε''), which relates to the ability of food to convert the absorbed microwave energy into heat (Chandrasekaran, Ramanathan, & Basak, 2012). Loss tangent (tan $\delta = \varepsilon''/\varepsilon'$) summarizes the dielectric properties of a material as the ratio of dielectric loss factor to the dielectric constant. These properties determine, among other factors, the depth of penetration of microwaves into food. Penetration depth is defined as the thickness of an infinite slab at which the microwave energy drops to 1/*e* (Euler number e = 2.718) times or 36.8% of the incident energy. Dielectric properties also help determine the ratio of energy reflected and transmitted through food, as well as the optimal frequency of microwave to be used for the heating of the food product. This has important implications in the design of products, processes and equipment that use microwave heating technology. For instance, knowledge of the depth of penetration (d_p) of microwaves helps in determining optimal geometry of the applicator to enable uniform heating of a product. When the applicator tube diameter is smaller than half the penetration depth, much of the incident microwave energy may not get absorbed by the product (Tuta & Palazoğlu, 2016). As a rule of thumb, the product dimension or in the case of continuous flow microwave processing, the applicator tube diameter is set to about 2 to 2.5 times the penetration depth (Buffler, 1993) to enable favorable focusing of energy in the center of the tube where product velocity is the

maximum (Salvi, Boldor, Aita, & Sabliov, 2011) which facilitates uniform heat distribution. However, the exact dimensions of the applicator tube should be confirmed by experimental validation. That way the maximum operating diameter (MOD), which is the diameter of the applicator in which the value of the electromagnetic field in the center is the same as in the interface between food material and tube, can be derived. The maxima of the MOD as a function of the dielectric properties can be used to assess the feasibility of using microwaves for a product (Coronel, 2006).

The measurement of dielectric properties has been generally done using an open-ended coaxial probe for its simplicity and compatibility with a wide range of materials (Stuchly, Athey, Samaras, & Taylor, 1982). Open-end probes allow measurements at a wide range of frequencies and temperatures in a relatively simple setup. The wide range of frequencies allows the exploration of resonant and critical frequencies for a given product at different temperatures. Critical frequency (f_c) is the frequency at which the dielectric loss factor is the highest and above which there is decrease in energy conversion to heat (Nelson & Trabelsi, 2012). The critical frequency, along with information on the ratio of reflected and transmitted energy (which is also the loss tangent) over a wide range of temperatures, is useful in designing energy-efficient processes that target maximum utilization of incident microwave energy to heat foods.

Dielectric properties of several vegetables and related products such as cucumber, carrot, radish, turnip, mushrooms, sweet potato, and tomato among many others, have been reported (Brinley, Truong, Coronel, Simunovic, & Sandeep, 2008; Funebo & Ohlson, 1999; Peng, Tang, Jiao, Bohnet, & Barrett, 2013; Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010, Kent 1987). The dielectric properties of red bell peppers acidified with citric acid were studied earlier (Koskiniemi, Truong, McFeeters, & Simunovic, 2012) along with the effects of acid and salt

levels, and soaking time on the dielectric properties. The product formulation with the highest loss tangent, and optimum soaking time for achieving complete acidification was selected based on information on uniformity in heat distribution (Koskiniemi, Truong, Simunovic, & McFeeters, 2011). However, acetic acid in the form of vinegar is the more commonly used acidifying agent in preserving red bell peppers (Péréz-Diáz et al., 2013). There also exists previous work on models (Calay, Newborough, Probert, & Calay, 1994; Funebo & Ohlson, 1999; Sun, Datta, & Lobo, 1995) that enable prediction of dielectric properties of single-phase (Brinley et al., 2008) and multi-phase (Álvarez, Fayos-Fernández, Monzó-Cabrera, Cocero, & Mato, 2017) food systems based on known factors such as the composition and temperature mainly, and additionally the volume fractions of components in multi-phase food systems (Álvarez et al., 2017). So far, there is no information on the factors affecting the dielectric properties of red bell peppers acidified with acetic acid, or any model for predicting the same.

The thermal properties such as specific heat capacity, and thermal conductivity are used to estimate the heating and cooling rate of foods in conventional heating (Raghavan, Orsat, & Meda, 2005) when heat is transferred to and from the product by convection and conduction. Specific heat capacity (c_p) is defined as the quantity of heat energy (J/KJ/Cal) required to raise the temperature of unit mass (g/Kg) of a material by 1 degree (K/°C) at constant pressure. c_p is an additive property and is directly dependent on the composition and temperature of food. It can be predicted using empirical equations if the proximate composition is known. Choi & Okos (1986) have developed predictive equations for calculating specific heat capacity of each food component as a function of temperature. The c_p of a composite food containing a mixture of water, protein, carbohydrates, fat, fiber, and ash, can be calculated by adding the products of specific heat capacities and mass fractions of the individual components. However, the values

obtained theoretically are reported to contain ± 6% error for temperatures between -40°C and 150°C. Calorimetric methods are typically used to determine the specific heat capacity of materials more accurately. Due to its heavy dependence on the composition, c_p is easily alterable by simply changing the composition of a product. As c_p is the negative reciprocal of the slope of an enthalpy vs temperature curve, it is inversely related to the heating rate. Lower heat capacities are desirable for achieving faster heating rates, and consequently better quality. Longer heating times are known to deteriorate the sensorial and nutritional quality of food (Arjmandi et al., 2017; Huang & Bourne, 1983). Red bell peppers contain 92.2% water (USDA, 2019), and lower proportions of carbohydrates, ash, lipids, and proteins. Water has the highest c_p of 4176.6 J/kg °C at 20°C, compared to other components in food (Rao, Rizvi, & Datta, 2005).

The thermal properties of many vegetables have been found in databases (ASHRAE, 2006; Nesvadba et al., 2004) that includes data for peppers in general without any specifics on the type. To our knowledge, so far, Ali, Ramaswamy, & Awuah (2002) and Kumar, Coronel, Simunovic, & Sandeep (2008) are the only works that have reported specific heat capacities for bell peppers, measured experimentally across a range of temperatures, but not red bell peppers specifically.

This work aims to characterize the dielectric and thermal properties of fresh and acidified red bell peppers including dielectric constant, dielectric loss factor, and specific heat capacity, to guide product and process design. Additionally, enabling the prediction of these properties based on the known composition and processing parameters (temperature, frequency) will be useful in reducing the costs associated with measurement and possibly promote the consideration of microwave technology for the manufacture of acidified red bell peppers.

3.3. MATERIALS AND METHODS

3.3.1. Determination of dielectric properties

Brines of different compositions were prepared by varying the levels of vinegar (20% acetic acid; commercial processor) and salt (purity ≥99.5%; Sigma Aldrich Cat# S-7653). Five levels of acetic acid, and four levels of salt ranging from 0% to 4% were tested to study their effects on dielectric properties. Table 3.2 elucidates the various combinations of acetic acid and salt used to prepare the brines.

Red bell peppers (26 fruits) from a single lot were procured, rinsed under tap water, cored, and destemmed, and then homogenized to a slurry in a Waring blender for 2 min at speed 5. The resulting fresh red bell pepper homogenate was combined with each of the brines (Table 3.2) in a ratio of 55:45 by volume. These red bell pepper homogenates were stored in a freezer at -18°C ± 1°C and thawed at 4°C overnight prior to the day of analyses. Table 3.3 elucidates the compositions of various red bell pepper homogenates tested in the study. To understand lot-to-lot variation, red bell peppers from three independent lots were used to replicate a single formula of acidified red bell peppers containing 2% salt and 1% acetic acid at equilibrium (Table 3.3).

The dielectric properties of the red bell pepper homogenates thus prepared were determined with a network analyzer (HP 8753C, Agilent Technologies, Palo Alto, California) using an open-ended coaxial probe (HP 85070B, Agilent Technologies, Palo Alto, California). The system was calibrated with air, short block, and deionized water. Each sample was taken in the sample holder and placed in an oil bath (Model RTE111, Neslab Instruments Inc, Newington, NH). Measurements were made at 15°C intervals from 20°C to 95°C. Dielectric properties of each sample were determined by averaging two measurements of the same sample.
Depth of penetration of microwaves was calculated using the expression –

$$d_p = \frac{c\sqrt{2}}{2\Pi f\sqrt{\varepsilon'[1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 - 1]}} \quad \text{Eq. (3.1)}$$

where c = 3.0 x 10^8 m/s and f = frequency (Hz).

The proportions of reflected and transmitted power were obtained using the following equations-

$$P_r = \left(\frac{\sqrt{\varepsilon'} - 1}{\sqrt{\varepsilon'} + 1}\right)^2 \quad \text{Eq. (3.2)}$$

$$P_{trans} = 1 - P_r \quad \text{Eq. (3.3)}$$

where P_r is proportion of reflected power and P_{trans} is the proportion of transmitted power.

3.3.2 Determination of electrical conductivity

The electrical conductivities of fresh and acidified red bell pepper homogenates (Table 3.3) were measured using two electrodes with different cell constants (K=1.0 cm^{-1}; Accumet 13-620-100, and K=10.0 cm^{-1}; Accumet 13-620-166, Fisher Scientific) connected to a potentiometer (Accumet XL500, Fisher Scientific). The electrodes were calibrated using 1.413 mS/cm, 12.880 mS/cm, and 50.00 mS/cm standards. At any time during the study, the standardization factors were > 0.95. Samples (~20 ml) were taken in 50 ml conical tubes and heated in an Eppendorf Thermomixer R with mixing at 300 rpm to measure conductivities at temperatures from 25°C to 75°C (at 10°C intervals). Even though automatic temperature compensation was applied for all the measurements, a thermocouple type T was used to accurately measure the temperature of the samples.

The contribution of ionic migration to the dielectric loss factor also known as ionic loss was calculated using Eq.3.6.

$$\varepsilon''_{\sigma} = \frac{1.80\sigma}{f} \qquad \text{Eq. (3.4)}$$

where σ = electrical conductivity (mS/cm) and f = frequency (GHz)

3.3.3. Determination of specific heat capacity

Red bell peppers (3 fruits each) were procured from three different sources, rinsed, and dried with a paper towel. A DSC 6000 differential scanning calorimeter (PerkinElmer, IL, USA) was used in conjunction with a cooling system (Intracooler II, PerkinElmer, IL, USA). Temperature and heat flow calibrations were carried out using Indium (0219-1207, PerkinElmer, IL, USA) resulting in a peak onset = 156.32°C and delta H = 28.0568 J/g, which are just 0.1% and 1.4% deviating from the expected values. This was followed by a baseline run using an empty aluminum pan (BO143017, PerkinElmer, IL, USA) of known weight, which was crimp-sealed using another pan of the same type. A reference sapphire (0219-1483, PerkinElmer, IL, USA) disk with known weight was sealed within a similar aluminum pan, and its heat flow was used to calibrate the DSC. Red bell peppers were chopped finely just prior to analysis and sealed within aluminum pans. The weight of red bell pepper samples taken was ±0.5 mg from the weight of sapphire reference i.e., 8.85 mg ±0.5 mg. For all the runs, i.e., baseline, reference, and samples, heat flow was measured at sample temperatures from 30°C to 101°C at a heating rate of 20°C/min with nitrogen gas purged at 20 ml/min. The samples were analyzed in triplicate for each fruit, and in a random order. Pyris software version 3 (PerkinElmer, IL, USA) was used to obtain the specific heat capacity curve after accounting for the heat flow of empty pan (baseline) and reference curve (sapphire). The specific heat curve was obtained by calculating the area under the heat flow curve as a function of temperature.

3.3.4. Development of predictive models

Statistical models to enable prediction of loss tangent were developed using acetic acid and salt contents, temperature, frequency, and electrical conductivity as independent variables. Multiple regression analysis was used to build the model, and a reduced model was finalized after removing insignificant main effects ($p>0.05$) by following common effect principles. Due attention was paid to ensure that error assumptions were met by using a logarithmic transformation. Errors with prediction were calculated using a cross validation method, and prediction accuracy was reported as (1-error)%. The statistical design is summarized in Table 3.4.

Response (dependent) variable: Loss tangent

Proposed model form for the full factorial design:

Full model –

$$\log Y = \mu + S + A + T + F + SA + ST + SF + AT + AF + TF + SAT + SAF + STF + AT + SATF + \varepsilon_{sample} + \varepsilon_{satf}$$

where,

log Y = log (loss tangent)

S = fixed effect of salt level

A = fixed effect of acetic acid level

T = fixed effect of temperature

F = fixed effect of frequency

ε_{sample} = error related to repeated measurement of each sample; assumed to be independent and identically distributed normally with mean 0 and variance σ^2_{sample}

ε_{satf} = error term that is assumed to be independent and identically distributed normally with mean 0 and variance σ^2

The other terms represent all possible interaction effects.

3.3.5. Statistical analyses

All statistical analyses were carried out using JMP Pro 15.2.0 (SAS Inc., Cary, NC). Regression analysis was used to correlate specific heat capacity with temperature, and multiple regression analysis was used to understand the changes in electrical conductivity as a function of temperature, acetic acid and salt levels. A type I error rate α= 0.05 was considered for all hypothesis tests involved.

3.4. RESULTS AND DISCUSSION

3.4.1. Dielectric properties of fresh and acidified red bell pepper homogenates

The analysis of dielectric properties of fresh and acidified red bell pepper homogenates (Table 3.3) revealed that the loss tangent significantly ($p<0.05$) increased with salt concentration and temperature (Figures 3.1 and 3.2). This is possible due to increase in dielectric loss factor and decrease in dielectric constant with higher temperatures and salt contents, which is consistent with previous work on other vegetables (Funebo & Ohlson, 1999; Koskiniemi et al., 2012; Kumar et al., 2008; Sipahioglu & Barringer, 2003). However, the effect of acetic acid on the loss tangent was not significant ($p>0.05$). This is likely because acetic acid is weakly dissociating in nature, so its binding with water (and causing a decrease in free moisture) or effect on ionic concentration is not profound. The amount of free moisture has been found to change the relationship between dielectric properties and temperature (Funebo & Ohlson, 1999; Sipahioglu & Barringer, 2003). It was also observed that the range of loss tangents of the homogenates was

higher when measured at 915 MHz than at 2450 MHz. The loss tangents obtained for acidified red bell peppers (1% acetic acid and 1% salt) in this study is comparable to those reported by Koskiniemi et al. (2012) for red bell peppers acidified with 1% citric acid and 1% salt.

Similarly, the dielectric loss factor of fresh red bell pepper homogenate (0% acetic acid and 0% salt) was comparable with that reported by Kumar et al. (2008), but the dielectric constant in this study which was higher at 20°C underwent a steeper decrease with temperature. This is probably due to higher moisture content of the red bell peppers used in this study. Brinley et al. (2008) have shown dielectric constant to be higher when moisture content was higher in sweet potato purees.

The changes in depth of penetration (d_p) of microwaves with the composition and temperature of red bell pepper homogenates are depicted in Figure 3.3. The d_p dropped by about 50% upon adding 1% salt and was observed to decrease when salt was increased further. At 4% salt, the d_p was just slightly higher than zero cm. Beyond this level of salt, suitability for microwave processing may be limited. Ideally, for such a multi-phase product containing strips of red bell peppers suspended in brine, a higher d_p would be favorable to have a wider applicator tube that would allow for conveying bigger particulates with minimum damage to their physical integrity. With the red bell pepper strips being 2.5 cm long in this study, a product with a d_p of at least 1 cm would be ideal. This includes acidified red bell peppers containing 0% to 4% acetic acid and about 1% salt, processed at 915 MHz. Though that can be set as a target for process design, sensory acceptability will need to be given primary consideration. Another suggested approach would be to mitigate the resulting focusing effects on the surface by having helical tubes (Gentry & Roberts, 2005; Zhang et al., 2021) in the process to facilitate uniform heat distribution. As expected from Eq.3.1, the d_p was higher at 915 MHz.

Energy efficiency is an important component of sustainable food production, which has become a consumer expectation especially from clean label foods. Figure 3.4 shows the proportion of incident power that got transmitted into fresh and acidified red bell pepper homogenates averaged across temperatures and frequencies. The transmitted power was significantly ($p<0.05$) impacted by the salt but not the acetic acid content. It was noted that the transmitted power was less than 50% of the incident power in general. This information is especially insightful to guide process design as the absorbed power can be manipulated by equipment design aspects such as cavity size with respect to the load (food) volume, position of load in the cavity, cavity material, and power supplied by magnetron (Buffler, 1993). Peanut beverages with a similar loss tangent (~ 0.25) were found to absorb up to 75% of incident power from a 5 kW system (Sabliov et al., 2008), which is reassuring. That said, simulations and actual experimental validation will guide equipment design and process optimization beyond this point.

3.4.2. Electrical conductivity of fresh and acidified red bell pepper homogenates

Figure 3.5 summarizes the changes in electrical conductivity with temperature and composition (acetic acid and salt) of red bell pepper homogenates. The regression equations representing the relationship between electrical conductivity and temperature for each treatment combination of acetic acid salt are also displayed.

The electrical conductivity increased significantly ($p<0.05$) with temperature and salt concentration (Figure 3.6), which is also evident from the slopes in the equations. However, the effect of acetic acid was much lower and not significant ($p>0.05$) on electrical conductivity. This is similar to the non-significant effect of acetic acid on loss tangent observed earlier in section 3.1, due to its poor contribution to the total ionic concentration (Ramaswamy, Marcotte, Sastry, Abdelrahim, & Fryer, 2014; Srivastav & Roy, 2014). The findings of this study relating to the

linear increases in conductivity as a function of temperature and salt content, are in line with those observed in previous studies (Adams & Hall, 1931; Icier & Ilicali, 2005; Pedersen, Feyissa, Kavli, & Frosch, 2016; Quist & Marshall, 1968; Sarang, Sastry, & Knipe, 2008; Srivastav & Roy, 2014; Wang & Sastry, 1993; Zareifard, Ramaswamy, Trigui, & Marcotte, 2003). The possible reasons for the minimal contribution to conductivity from fresh red bell peppers (0% acetic acid and 0% salt) could be the higher viscosity and electrical neutrality of cellular materials (Rao et al., 2005). Additionally, the positive slopes indicating increases in conductivity and dielectric loss factor with temperature may support the possibility that conductivity and loss factor could be correlated in acidified red bell peppers (shown later in this study).

3.4.3. Specific heat capacity of fresh red bell peppers

The loss tangent of fresh red bell peppers was found to be very low (~0.2), which likely makes it the slower heating component than brine. Thus, information on the specific heat capacity of fresh red bell peppers would be useful to understand the worst-case scenario in energy requirement and heating rate. DSC of fresh red bell pepper revealed that temperature significantly ($p<0.05$) increased the specific heat capacity. Additionally, the DSC thermograms did not reveal any thermal events i.e., heat-involved physical or chemical changes in the fresh red bell peppers. The relationship between c_p and temperature could be summarized as -

$$c_p = 1.7542 + 0.0482T - 0.0003T^2 \qquad \text{Eq. (3.5)}$$

with $R^2 = 0.986$, where c_p is specific heat capacity expressed in J/g°C at temperature T expressed in °C. Based on the chemical composition of red bell peppers (Table 3.1), it could be hypothesized that the c_p of red bell peppers may be close to that of water. However, the c_p of red bell peppers was 2.5982 J/g°C at 20°C, which is about half of that of water. This result is also slightly lower than 3.714 J/g°C and 3.943 J/g°C at 20°C obtained for green peppers (Ali et al,

2002) and bell peppers respectively (Kumar et al., 2008) respectively, which is possible due to differences in the varieties of peppers used.

With this information, the thermal energy requirement can be calculated by substituting for T, and heating rate during experimental validation can be obtained by using the following formula –

$$\frac{\Delta T}{\Delta t} = \frac{P_{abs}}{14.7 \times V \times c_p \times \rho} \quad \text{Eq. (3.6)}$$

where $\Delta T/\Delta t$ is the heating rate in °C/s, P_{abs} is the absorbed power in Watts (or J/s), V is the volume of food in ml, c_p is the specific heat capacity in J/g°C, and ρ is the density of food in g/ml.

3.4.4. Predictive model for dielectric properties of acidified red bell peppers

Although the dielectric properties of 20 different compositions of acidified red bell pepper homogenates have been characterized in this study with the goal of laying down the basic knowledge required for process design using microwave technology, the equipment involved in such characterization is expensive (~$25,000 for refurbished equipment). To help reduce the cost burden associated with the consideration of microwave technology for the manufacture of acidified red bell peppers, this work has developed a model for the determination of loss tangent. This model could be used when the temperature, composition and electrical conductivity are known. This model will be applicable for acidified red bell peppers with 0-4% acetic acid, 0-4% salt, and pack ratio of 55:45. The model used for the theoretical determination of loss tangent when the composition is known is given in Eq.3.7. When the composition is unknown or more

complex, and the electrical conductivity is known, loss tangent could be determined using Eqs.3.8.

$$\log tan\delta = -2.00 + 0.015T + 0.36F + 0.66S - 0.15S^2 + 0.10SF - 0.03S^2F + 0.003ST - 0.001S^2T + 0.003TF - 0.001TFS \quad \text{Eq. (3.7)}$$

$$tan\delta \; at \; 915 \text{ MHz} = -0.05 + 0.03\sigma \quad \text{Eq. (3.8a)}$$

$$tan\delta \; at \; 2450 \text{ MHz} = 0.11 + 0.01\sigma \quad \text{Eq. (3.8b)}$$

where A = acetic acid (%), S = salt (%), F = frequency (MHz), T = temperature (°C), $tan\delta$ = loss tangent, and σ= electrical conductivity (mS/cm). The value for F = 1 when 915 MHz, and F = 0 when 2450 MHz is to be used. The prediction accuracies for these models are 86% (Eq.3.7), 81% (Eq.3.8a), and 88% (eq.3.8b).

The ranges of salt and acetic acid levels used in this study are relevant and representative of those generally used in acidified vegetables. While the electrical conductivities of other fresh produce have been determined (Icier & Ilicali, 2005; Sarang et al., 2008; Wang & Sastry, 1997) this is the first study to our knowledge that has analyzed the electrical conductivity of red bell peppers in fresh and acidified forms. It is to be noted that the electrical conductivities of acidified red bell pepper measured in this study could differ depending on the vegetable:brine ratios and particle size (Zareifard et al., 2003), thus may be slightly deviating from that of non-homogenized acidified red bell peppers.

The next crucial step in process design is the determination of target temperature and holding time. The temperature and holding time are determined and chosen to inactivate microorganisms of public health significance in most cases. However, knowing that acidified red bell peppers are susceptible to softening, enzymes such as polygalacturonase may be chosen as

targets for inactivation. Some information on the extraction protocols and activities of polygalacturonase in fresh red bell peppers is given in appendix 3. Also included are experimental findings on the acidification rate of red bell peppers (appendix 1) and pH values of different formulas of acidified red bell peppers (appendix 2) to provide basis for product design and operational decisions.

3.5. CONCLUSION

Thus, the dielectric and thermal properties of fresh and acidified red bell peppers critical to guide product and process design using microwave technology were laid down by this study. These along with data from pilot scale runs can be used to assess the feasibility of processing acidified red bell peppers with microwaves using criteria proposed by Coronel (2006). The feasibility of continuous flow microwave processing of a multiphase product (with a similar range of loss tangent), such as *salsa con queso* validated in previous work (Kumar et al., 2007), shows that there exists a possibility for the same with acidified red bell peppers. Similar to such feasibility studies, pilot scale runs are recommended for further characterization (such as absorbed power and heating rate) and optimization of equipment and process. It is important to keep in mind that formulation of the product should be done in accordance with consumer expectations and may be only slightly modified to suit the requirements of the process. Additionally, statistical models enabling prediction of loss tangent from known parameters such as composition (acetic acid and salt) and electrical conductivity were developed foreseeing the cost implications of such characterization. However, the models need to be further enhanced by ensuring accurate measurement using the open-ended coaxial probe, increasing replications, and accounting for different pack ratios (peppers:brine). Higher pack ratios could cause changes in the loss tangent due to decrease in moisture content and increase in viscosity. Thus, this work

lays the foundation for the development of clean label acidified red bell peppers manufactured using continuous flow microwave technology.

TABLES

Table 3.1. Chemical composition of red bell peppers

Component	Mass fraction
Water	0.9220
Carbohydrates	0.0603
Lipids	0.0030
Proteins	0.0099
Ash	0.0047

Table 3.2. Compositions of various brines prepared for this study.

Brine formulations		**Sodium chloride (% w/w)**			
		0%	**2.22%**	**4.44%**	**8.88%**
Acetic acid (% w/w)	**0%**	N/A	Formula ID: B01	Formula ID: B02	Formula ID: B04
	1.11%	Formula ID: B0.50	Formula ID: B0.51	Formula ID: B0.52	Formula ID: B0.54
	2.22%	Formula ID: B10	Formula ID: B11	Formula ID: B12	Formula ID: B14
	4.44%	Formula ID: B20	Formula ID: B21	Formula ID: B22	Formula ID: B24
	8.88%	Formula ID: B40	Formula ID: B41	Formula ID: B42	Formula ID: B44

Table 3.3. Compositions of red bell pepper homogenates characterized in this study.

Red bell pepper homogenate formulations		**Sodium chloride (% w/w)**			
		0%	**1%**	**2%**	**4%**
Acetic acid (% w/w)	**0%**	Formula ID: P00	Formula ID: P01	Formula ID: P02	Formula ID: P04
	0.5%	Formula ID: P0.50	Formula ID: P0.51	Formula ID: P0.52	Formula ID: P0.54
	1%	Formula ID: P10	Formula ID: P11	Formula ID: P12 (Prepared in triplicate)	Formula ID: P14
	2%	Formula ID: P20	Formula ID: P21	Formula ID: P22	Formula ID: P24
	4%	Formula ID: P40	Formula ID: P41	Formula ID: P42	Formula ID: P44

Table 3.4. Summary of statistical design used in this study.

Variable name	**Notation**	**Number of levels**	**Details of levels**	**Variable type**
Salt (%)	S	4	s = 0, 1, 2, 4	Numeric continuous
Acetic acid (%)	A	5	a = 0, 0.5, 1, 2, 4	Numeric continuous
Temperature (℃)	T	6	t = 20, 35, 50, 65, 80, 95	Numeric continuous
Frequency (MHz)	F	2	f = 915, 2450	Numeric nominal

FIGURES

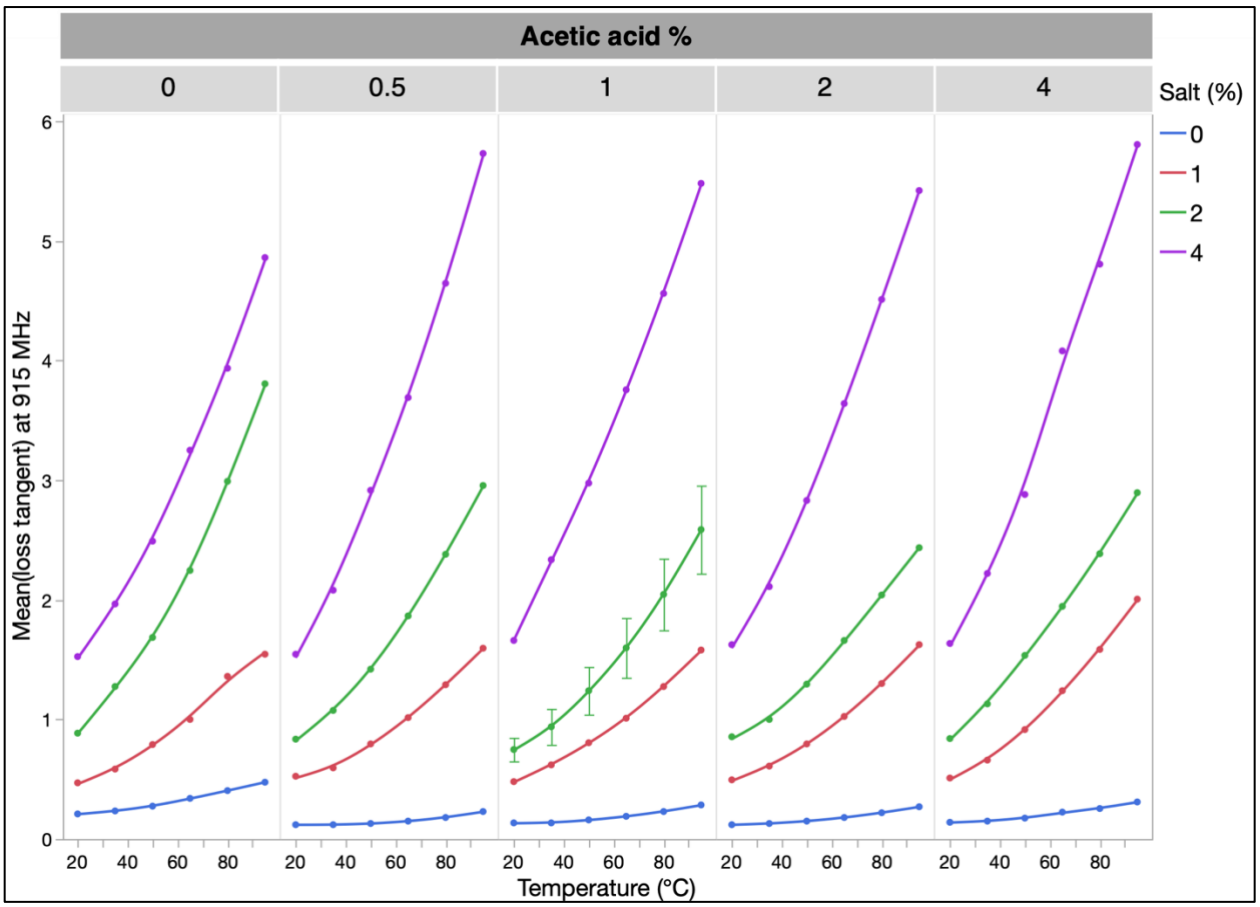

Figure 3.1. Changes in loss tangent as a function of temperature, acetic acid and salt concentrations at 915 MHz. Error bars represent variation due to three different lots of peppers tested (for 1% acetic acid and 2% salt) and random error.

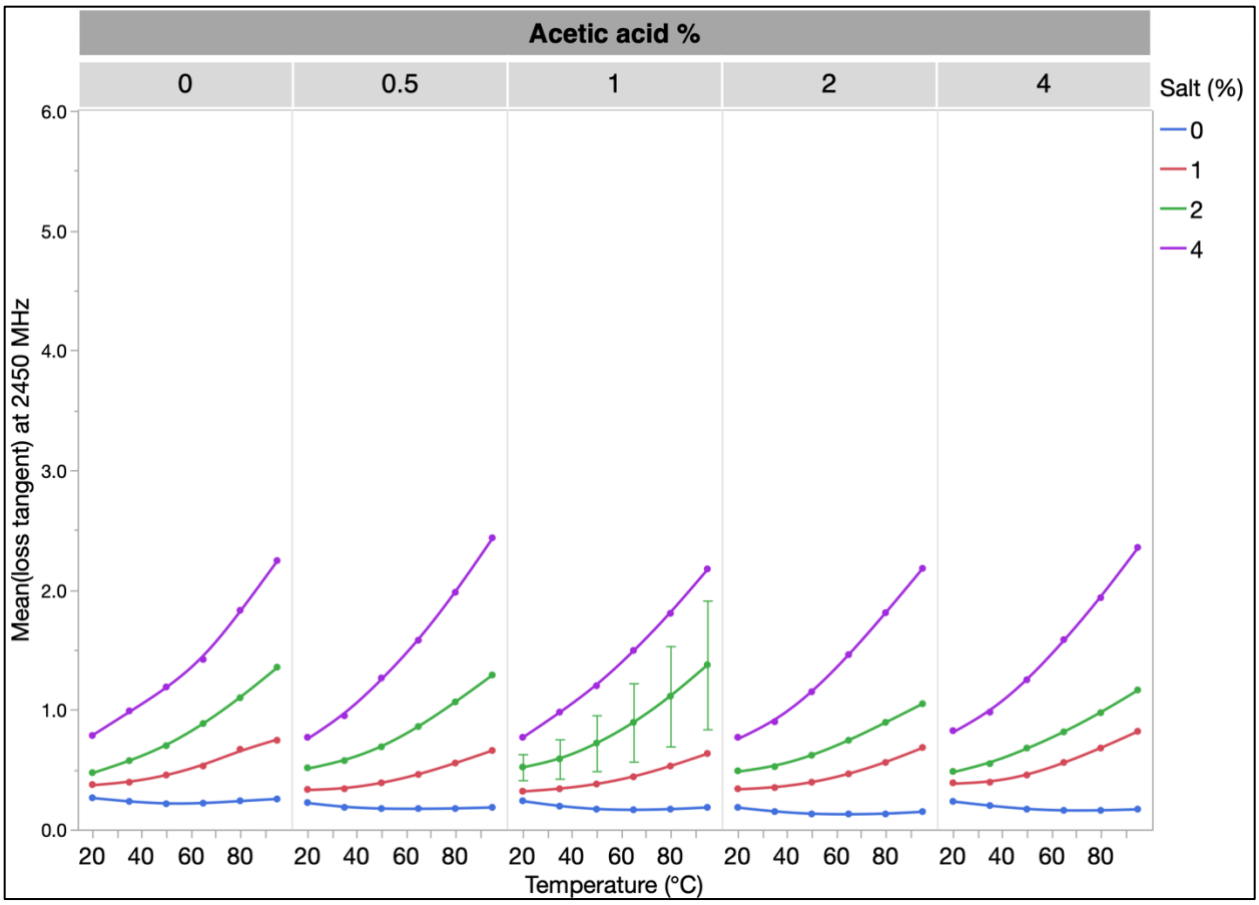

Figure 3.2. Changes in loss tangent as a function of temperature, acetic acid and salt concentrations at 2450 MHz. Error bars represent variation due to three different lots of peppers tested (for 1% acetic acid and 2% salt) and random error.

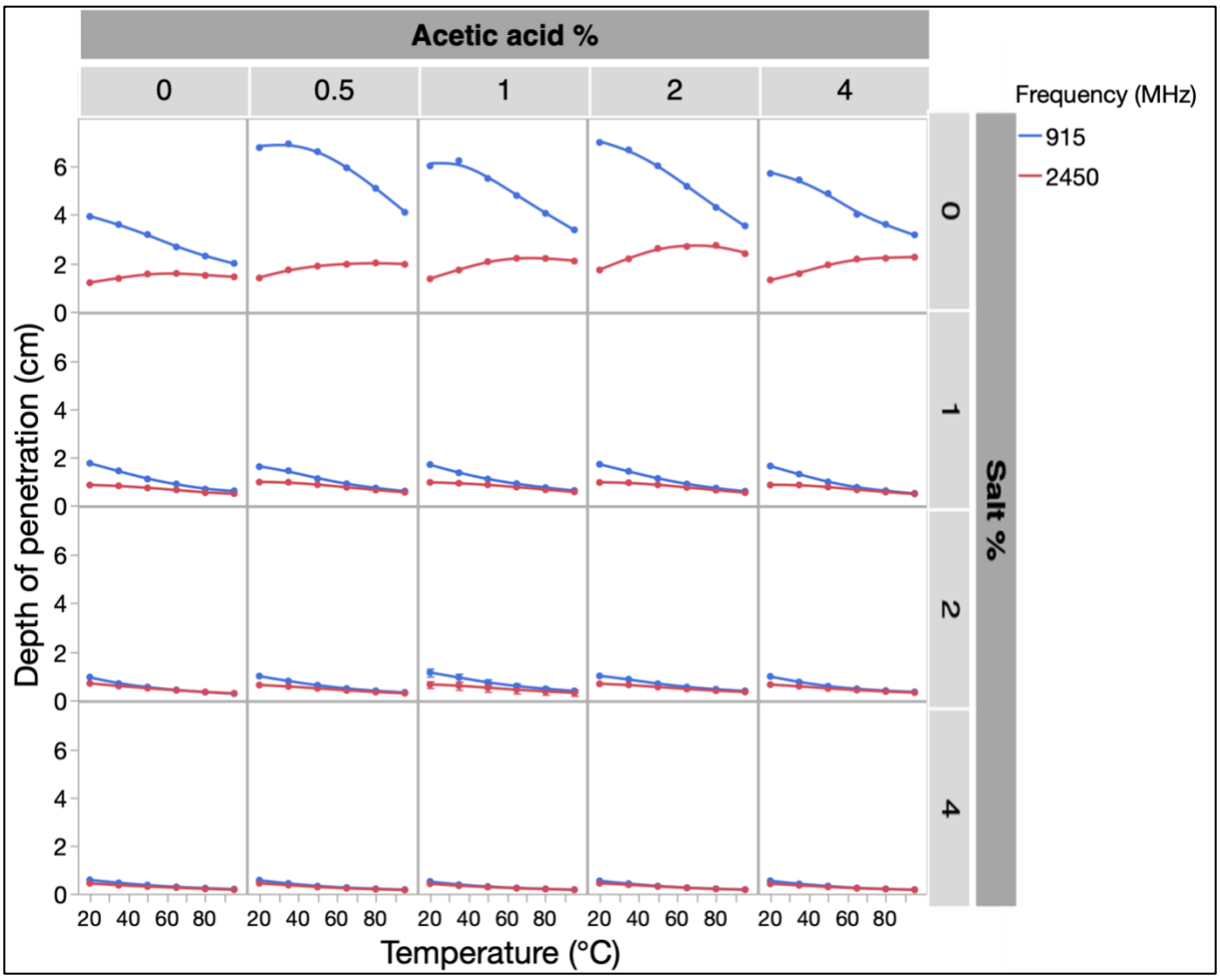

Figure 3.3. Changes in depth of penetration as a function of temperature and composition at 915 MHz and 250 MHz. Error bars represent variation due to three different lots of peppers tested (for 1% acetic acid and 2% salt) and random error.

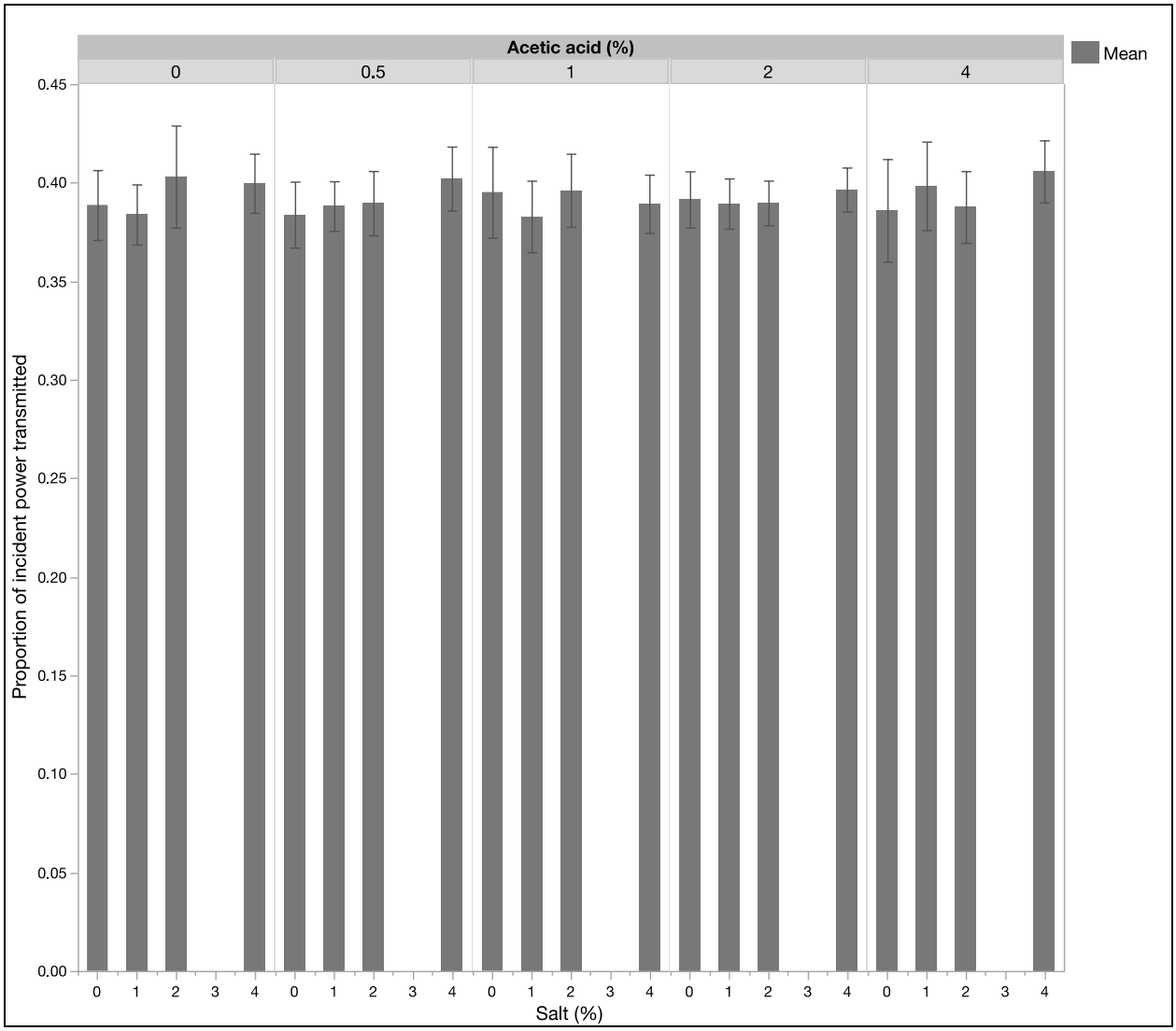

Figure 3.4. Proportions of transmitted power as a function of the composition of red bell pepper homogenates. Error bars represent variation due to temperature, frequency, three different lots of peppers tested (for 1% acetic acid and 2% salt), and random error.

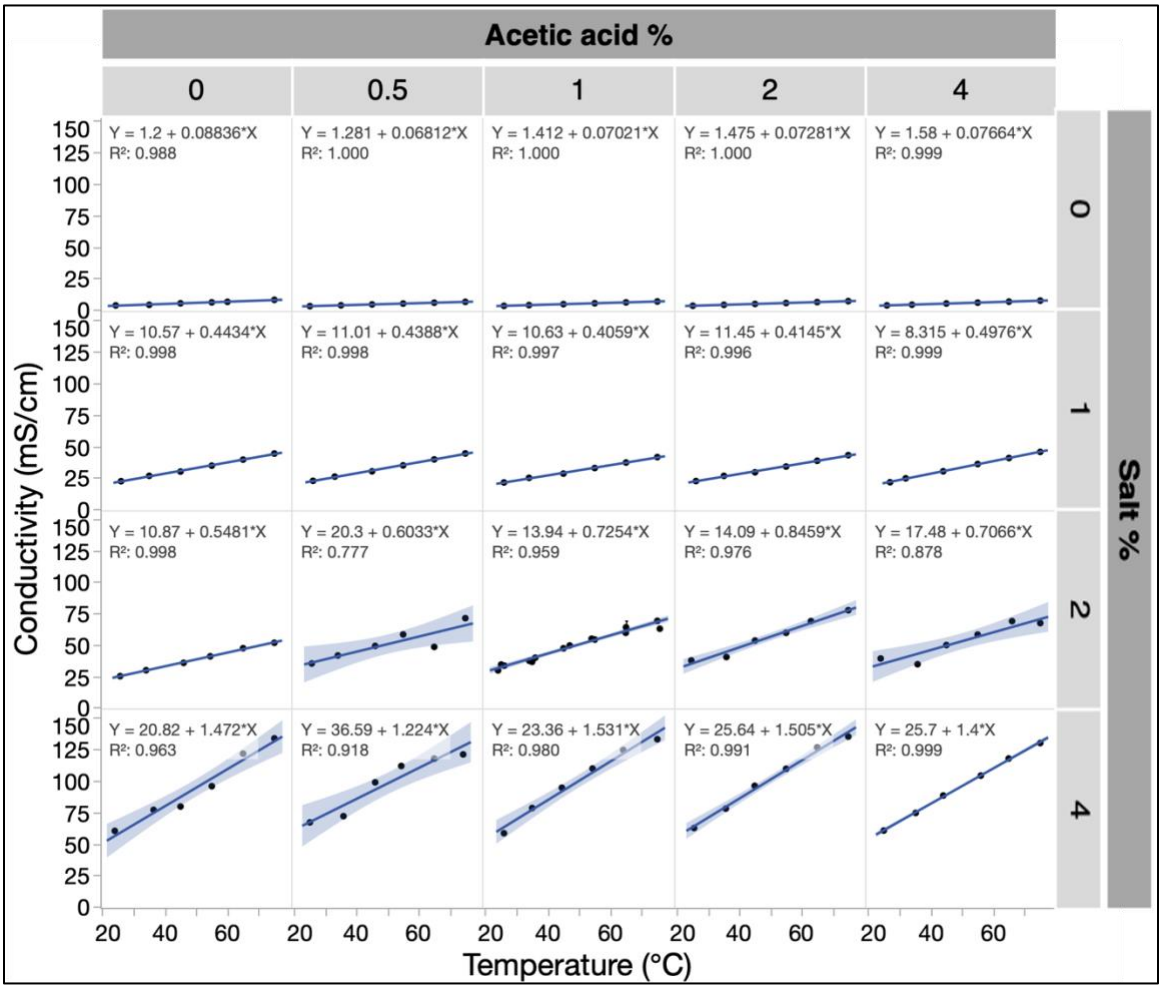

Figure 3.5. Changes in electrical conductivity due to the influence of temperature and composition of red bell pepper homogenates.

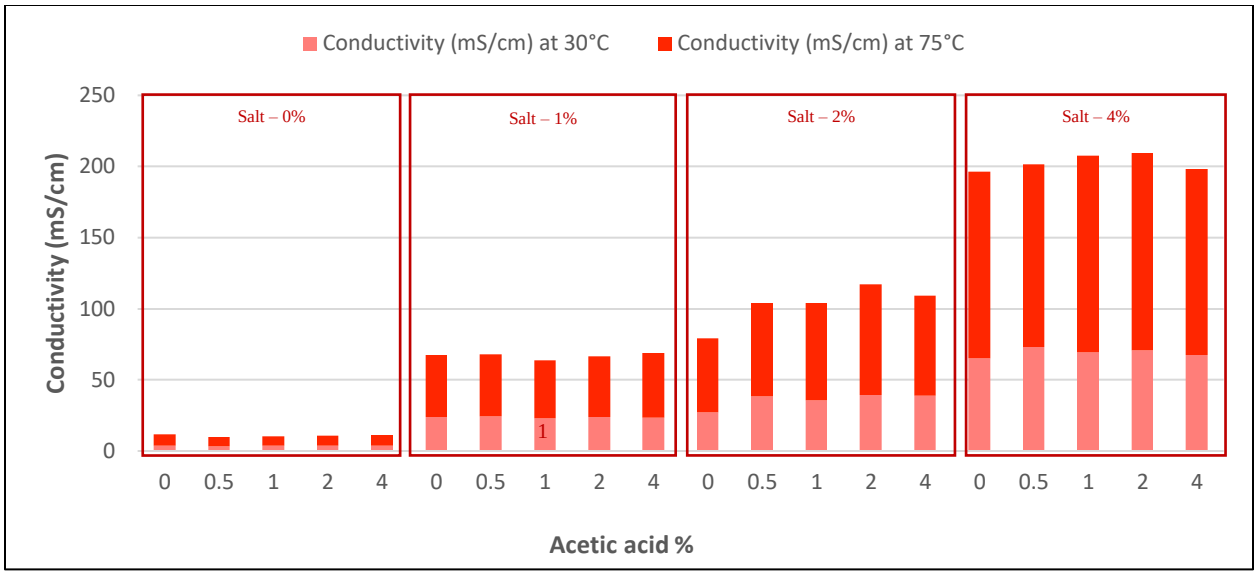

Figure 3.6. Electrical conductivities at 30°C and 75°C influenced by the composition of red bell pepper homogenates. Stacked bars for red bell pepper homogenate with 1% acetic acid and 2% salt represent the mean conductivity of three different lots of red bell peppers.

REFERENCES

Adams, L. H., & Hall, R. E. (1931). The Effect of Pressure on the Electrical Conductivity of Solutions of Sodium Chloride and of Other Electrolytes | The Journal of Physical Chemistry. *The Journal of Physical Chemistry*, *35*(8), 2145–2163.

Ali, S.D., Ramaswamy, H.S., & Awuah, G. B. (2002). Thermo-Physical Properties of Selected Vegetables as Influenced by Temperature and Moisture Content. *Journal of Food Process Engineering*, *25*(5), 417–433.

Álvarez, A., Fayos-Fernández, J., Monzó-Cabrera, J., Cocero, M. J., & Mato, R. B. (2017). Measurement and correlation of the dielectric properties of a grape pomace extraction media. Effect of temperature and composition. *Journal of Food Engineering*, *197*, 98–106.

Arjmandi, M., Otón, M., Artés, F., Artés-Hernández, F., Gómez, P. A., & Aguayo, E. (2017). Microwave flow and conventional heating effects on the physicochemical properties, bioactive compounds and enzymatic activity of tomato puree. *Journal of the Science of Food and Agriculture*, *97*(3), 984–990.

ASHRAE. (2006). Thermal Properties of Foods. *2006 ASHRAE Handbook: Refrigeration*, ASHRAE Handbook Refrigeration SI. American Society of Heating, Refrigeration and Air-Conditioning Engineers. Retrieved from https://books.google.com/books?id=touHPwAACAAJ

Breidt, F., Hayes, J., & McFeeters, R. F. (2007). Determination of 5-Log Reduction Times for Food Pathogens in Acidified Cucumbers during Storage at 10 and 25°C. *Journal of Food Protection*, *70*(11), 2638–2641.

Breidt, F., Kay, K., Cook, J., Osborne, J., Ingham, B., & Arritt, F. (2013). Determination of 5-Log Reduction Times for Escherichia coli O157:H7, Salmonella enterica, or Listeria monocytogenes in Acidified Foods with pH 3.5 or 3.8. *Journal of Food Protection*, *76*(7), 1245–1249.

Breidt, F., Kay, K., Osborne, J., Ingham, B., & Arritt, F. (2014). Thermal Processing of Acidified Foods with pH 4.1 to pH 4.6. *Food Protection Trends*, *34*(2), 132–138. Des Moines, United Kingdom: Allen Press Inc.

Brinley, T. A., Truong, V. D., Coronel, P., Simunovic, J., & Sandeep, K. P. (2008). Dielectric Properties of Sweet Potato Purees at 915 MHz as Affected by Temperature and Chemical Composition. *International Journal of Food Properties*, *11*(1), 158–172. Taylor & Francis.

Buffler, C. R. (1993). *Microwave cooking and processing: Engineering fundamentals for the food scientist*. New York: New York : Van Nostrand Reinhold, [1993]. Retrieved from https://catalog.lib.ncsu.edu/catalog/NCSU810523

Calay, R. K., Newborough, M., Probert, D., & Calay, P. S. (1994). Predictive equations for the dielectric properties of foods. *International Journal of Food Science & Technology*, *29*(6), 699–713.

Chandrasekaran, S., Ramanathan, S., & Basak, T. (2012). Microwave material processing—A review. *AIChE Journal*, *58*(2), 330–363.

Choi, Y., & Okos, M. (1986). Effects of temperature and composition on the thermal properties of food. In M. Le Maguer & P. Jelen (Eds.), *Food Engineering and Process Applications: Transport Phenomena* (Vol. 1, pp. 93–101). New York: Elsevier Applied Science Publishers.

Coronel (2006). *Continuous Flow Processing of Foods using Cylindrical Applicator Microwave Systems Operating at 915 MHZ* (Ph.D.). North Carolina State University, Raleigh, North Carolina.

Datta, A. K., & Anantheswaran, R. C., 1955-. (2001). *Handbook of microwave technology for food applications*. New York: New York: Marcel Dekker, [2001]. Retrieved from https://catalog.lib.ncsu.edu/catalog/NCSU1480702

Fajans, K., & Hassel, O. (1923). A new method for titration of silver and halogen ions with organic dyestuff indicators. *Zeitschrift fu¨r Elektrochemie und angewandte physikalische Chemie*, *29*, 495–500.

Fleming, H., McFeeters, R., & Breidt, F. (2001). Fermented and Acidified Vegetables. Compendium of Methods for The Microbiological Examination of Foods (pp. 521–532). Washington DC: American Public Health Association.

Funebo, T., & Ohlson, T. (1999). Dielectric Properties of Fruits and Vegetables as a Function of Temperature and Moisture Content Dielectric Properties of Fruits and Vegetables as a Function of Temperature and Moisture Content. *Journal of Microwave Power and Electromagnetic Energy*, *34*(1), 42–54. Taylor & Francis.

Gentry, T. S., & Roberts, J. S. (2005). Design and evaluation of a continuous flow microwave pasteurization system for apple cider. *LWT - Food Science and Technology*, *38*(3), 227–238.

Huang, Y. t., & Bourne, M. C. (1983). Kinetics of Thermal Softening of Vegetables. *Journal of Texture Studies*, *14*(1), 1–9.

Icier, F., & Ilicali, C. (2005). Temperature dependent electrical conductivities of fruit purees during ohmic heating. *Food Research International*, *38*(10), 1135–1142.

Kent, M. 1987. Electrical and dielectric properties of food materials: a bibliography and tabulated data. Science and Technology Publishers, London, UK.

Koskiniemi, C. B., Truong, V.-D., Simunovic, J., & McFeeters, R. F. (2011). Improvement of heating uniformity in packaged acidified vegetables pasteurized with a 915MHz continuous microwave system. *Journal of Food Engineering*, *105*(1), 149–160.

Koskiniemi, C., Truong, V. D., McFeeters, R., & Simunovic, J. (2012). Effects of Acid, Salt and Soaking Time on the Dielectric Properties of Acidified Vegetables. *International Journal of Food Properties—INT J FOOD PROP*, *16*(4).

Kumar, P., Coronel, P., Simunovic, J., & Sandeep, K. P. (2007). Feasibility of aseptic processing of a low-acid multiphase food product (salsa con queso) using a continuous flow microwave system. *Journal of Food Science*, *72*(3), E121-124.

Kumar, P., Coronel, P., Simunovic, J., & Sandeep, K. P. (2008). Thermophysical and Dielectric Properties of Salsa Con Queso and its Vegetable Ingredients at Sterilization Temperatures. *International Journal of Food Properties*, *11*(1), 112–126. Taylor & Francis.

McMurtrie, E. K., & Johanningsmeier, S. D. (2018). Quality of Cucumbers Commercially Fermented in Calcium Chloride Brine without Sodium Salts. *Journal of Food Quality*, *2018*. Retrieved from https://www.hindawi.com/journals/jfq/2018/8051435/

Nelson, S. O., & Trabelsi, S. (2012). Factors Influencing the Dielectric Properties of Agricultural and Food Products. *Journal of Microwave Power and Electromagnetic Energy*, *46*(2), 93–107. Taylor & Francis.

Nesvadba, P., Houška, M., Wolf, W., Gekas, V., Jarvis, D., Sadd, P. A., & Johns, A. I. (2004). Database of physical properties of agro-food materials. *Journal of food engineering*, *61*(4), 497–503. Oxford: Elsevier Ltd.

Nielsen, S. S. (2019). *Food Analysis Laboratory Manual*. Food Science Text Series (3rd ed.). Switzerland: Springer.

Pedersen, S. J., Feyissa, A. H., Kavli, S. T. B., & Frosch, S. (2016). An investigation on the application of ohmic heating of cold water shrimp and brine mixtures. *Journal of Food Engineering*, *179*, 28–35. Elsevier.

Peng, J., Tang, J., Jiao, Y., Bohnet, S. G., & Barrett, D. M. (2013). Dielectric properties of tomatoes assisting in the development of microwave pasteurization and sterilization processes. *LWT - Food Science and Technology*, *54*(2), 367–376.

Péréz-Diáz, I., Breidt, F., Buescher, R. W., Arroyo-Lo´pez, F. N., Jime´nez-Dı´az, R., Ferna´ndez, A. G., Gallego, J. B., et al. (2013). Fermented and Acidified Vegetables. In F. P. Downes & K. Ito (Eds.), Compendium of Methods for the Microbiological Examination of Foods (Fifth edition.). Washington, DC: APHA Press.

Peyre, F., Datta, A., & Seyler, C. (1997). Influence of the dielectric property on microwave oven heating patterns: Application to food materials. *The Journal of microwave power and electromagnetic energy*, *32*(1), 3.

Quist, A. S., & Marshall, W. L. (1968). Electrical conductances of aqueous sodium chloride solutions from 0 to 800.degree and at pressures to 4000 bars. *The Journal of Physical Chemistry*, *72*(2), 684–703. American Chemical Society.

Raghavan, V., Orsat, V., & Meda, V. (2005). Microwave Processing of Foods. *Stewart Postharvest Review*, *1*, 1–8.

Ramaswamy, H. S., Marcotte, M., Sastry, S., Abdelrahim, K., & Fryer, P. J. (Eds.). (2014). *Ohmic Heating in Food Processing*. Taylor & Francis Group.

Rao, M. A., Rizvi, S. S. H., & Datta, A. K. (2005). *Engineering properties of foods*. Boca Raton, Fla.: Boca Raton, Fla. : Taylor & Francis, 2005.

Salvi, D., Boldor, D., Aita, G. M., & Sabliov, C. M. (2011). COMSOL Multiphysics model for continuous flow microwave heating of liquids. *Journal of Food Engineering*, *104*(3), 422–429. Elsevier.

Sarang, S., Sastry, S. K., & Knipe, L. (2008). Electrical conductivity of fruits and meats during ohmic heating. *Journal of Food Engineering*, *87*(3), 351–356.

Sipahioglu, O., & Barringer, S. a. (2003). Dielectric Properties of Vegetables and Fruits as a Function of Temperature, Ash, and Moisture Content. *Journal of Food Science*, *68*(1), 234–239.

Sosa-Morales, M. E., Valerio-Junco, L., López-Malo, A., & García, H. S. (2010). Dielectric properties of foods: Reported data in the 21st Century and their potential applications. *LWT - Food Science and Technology*, *43*(8), 1169–1179.

Srivastav, S., & Roy, S. (2014). Changes in electrical conductivity of liquid foods during ohmic heating. *International Journal of Agricultural and Biological Engineering*, *7*(5), 133–138.

Stuchly, M. A., Athey, T. W., Samaras, G. M., & Taylor, G. E. (1982). Measurement of Radio Frequency Permittivity of Biological Tissues with an Open-Ended Coaxial Line: Part II - Experimental Results. *IEEE Transactions on Microwave Theory and Techniques*, *30*(1), 87–92. Presented at the IEEE Transactions on Microwave Theory and Techniques.

Sun, E., Datta, A., & Lobo, S. (1995). Composition-Based Prediction of Dielectric Properties of Foods. *Journal of Microwave Power and Electromagnetic Energy*, *30*(4), 205–212. Taylor & Francis.

Tuta, S., & Palazoğlu, T. (2016). Finite element modeling of continuous-flow microwave heating of fluid foods and experimental validation. *Journal of Food Engineering*, *192*.

USDA. (2019). Peppers, sweet, red, raw FDC ID: 170108. *USDA FoodData Central*. Database, . Retrieved January 27, 2022, from https://fdc.nal.usda.gov/fdc-app.html#/food-details/170108/nutrients

Wang, W. C., & Sastry, S. K. (1993). Salt diffusion into vegetable tissue as a pretreatment for ohmic heating: Electrical conductivity profiles and vacuum infusion studies. *Journal of food engineering*, *20*(4), 299–309.

Wang, W.-C., & Sastry, S. K. (1997). Changes in Electrical Conductivity of Selected Vegetables During Multiple Thermal Treatments. *Journal of Food Process Engineering*, *20*(6), 499–516.

Zareifard, M. R., Ramaswamy, H. S., Trigui, M., & Marcotte, M. (2003). Ohmic heating behaviour and electrical conductivity of two-phase food systems. *Innovative food science & emerging technologies*, *4*(1), 45–55. Elsevier Science.

Zhang, Y., Yang, H., Yan, B., Zhu, H., Gao, W., Zhao, J., Zhang, H., et al. (2021). Continuous flow microwave system with helical tubes for liquid food heating. *Journal of Food Engineering*, *294*, 110409.

Zhu, J., Kuznetsov, A. V., & Sandeep, K. P. (2007). Mathematical modeling of continuous flow microwave heating of liquids (effects of dielectric properties and design parameters). *International Journal of Thermal Sciences*, *46*(4), 328–341

CHAPTER 4: A SENSORY LEXICON TO DETERMINE THE QUALITY OF FRESH AND PRESERVED PEPPERS

4.1. ABSTRACT

Pepper fruits (*Capsicum annuum*) are economically important commodities worldwide due to their unique sensory profiles and rich antioxidant properties. With ongoing research efforts in optimizing the production and processing of peppers, there is a need for a standardized tool to evaluate the quality of peppers and its products. The objective of this work was to develop a sensory lexicon to characterize fresh and preserved peppers. A panel of 10 volunteers was recruited and trained in quantitative descriptive sensory analysis for a total of 37 hours. Commercially available fresh, pickled, and/or roasted peppers were used to establish definitions, methods of evaluation, and reference materials for each unique attribute; and a scale ranging from 0 to 15 was used for scoring attribute intensities. Commercially available fresh and preserved pepper samples (n=22) were evaluated by the panel in duplicate to validate the lexicon. Principal Component Analysis (PCA) was used to visualize differences among the products and attribute redundancies identified through analysis of correlations. A lexicon with 46 clearly defined terms that describe fresh, pickled, and roasted pepper products was developed. It is comprised of 14 aroma, 19 flavor, 9 texture, and 4 chemesthetic attributes. Smoky, burnt, and cooked tomato sensations were typical of roasted red bell peppers, while the floral attribute was characteristic of fresh red bell peppers, and vinegar, pungency, and spicy notes characterized pickled peppers. The lexicon enabled characterization and differentiation of a wide range of pepper products and lays the framework for its quality evaluation and improvement.

4.1.1. Practical Application

Breeders and processors are seeking technologies that could ensure desirable quality of fresh and processed peppers for an extended shelf life. This sensory lexicon serves as a basis for evaluating various strategies towards quality improvement, such as novel processing of pepper products.

4.2. INTRODUCTION

The global production of peppers (*Capsicum annuum*) was 36.1 million metric tons in 2020 (Statista, 2022). Peppers are among the top ten most cultivated vegetables in the world, because of their unique flavor and nutritional value. Peppers are rich in phenols, flavonoids, capsaicinoids (Loizzo, Pugliese, Bonesi, Menichini, & Tundis, 2015), and ascorbic acid that confer its antioxidant properties (Carvalho et al., 2015). Capsaicinoids are alkaloids that are unique to the *Capsicum* family that elicit trigeminal responses (Naves et al., 2019) that are often described as heat, burn, and numbing (Ward, 2016). The Scoville Heat Units (SHU) help to quantitatively express the highest dilution required for detection of heat in peppers (Scoville, 1912). Higher SHUs indicate higher capsaicinoid content that is characteristic of hot peppers. Peppers are popularly used both in fresh and preserved forms. Fresh peppers are used in domestic and food service kitchens either raw in salads and sandwiches or cooked as in salsa dips and curries. Preserved peppers, including roasted, brined, and canned forms, have found markets in both retail and food service as ingredients in sandwiches, pizzas, pastas, and other ready-to-cook and prepared dishes.

In the United States (US), the annual production of peppers amounts to 1.17 billion pounds (USDA NASS, 2021), of which just 93 million pounds of peppers are exported (USDA ERS, 2021). Peppers available in the US are largely imported from Mexico and Canada, at volumes more than 2.5 times higher than those domestically produced. Imports also include 177 million

pounds of preserved pepper products (USDA ERS, 2021). The domestic production volumes of bell and chile peppers experienced a steady decline from 2016 (USDA NASS, 2021) as a consequence of reduced acreage allocated for pepper cultivation due to increasing production costs and competition from international growers (Biswas, Guan, & Wu, 2018; Smoley, 2020). Federal bodies such as the U.S. Department of Agriculture (USDA) in collaboration with other research groups are initiating investigations on newer cultivation practices to reduce production costs and improve safety and quality of peppers (McCall, 2021). With the ongoing decline in domestic pepper production and increase in imports, the efforts of breeders and processors will play a crucial role in reversing the trend.

Besides conventional processing methods, research on novel processing technologies to enable sustainable production and improve quality, is gaining interest (Castillejo, Martínez-Zamora, & Artés-Hernández, 2022; Chen, Hu, Wang, Hu, & Cui, 2016; González-Saucedo et al., 2019). To study the impact of process changes, the quality of products needs to be evaluated to ensure that it meets expectations. With sensory quality having the most impact on consumer buying decisions (Hoppu, Puputti, & Sandell, 2021), a system to determine the sensory characteristics of fresh and processed pepper products will facilitate the efforts of breeding and processing sectors in making improved quality products available to consumers.

Early work on the flavor and texture of pepper products used instrumental techniques (Buttery, Seifert, Guadagni, & Ling, 1969; Conforti & Zinck, 2002; Huffman, Schadle, Villalon, & Burns, 1978; Jen & Robinson, 1984; Luning et al., 1994; Luning, de Rijk, Wichers, & Roozen, 1994; Luning, Yuksel, Vries, & Roozen, 1995; Papageorge, McFeeters, & Fleming, 2003; Xiao et al., 2010), while limited work exists on the sensory attributes. Luning et al. (1994) have been able to differentiate the flavor among fresh bell peppers at different ripening stages using a trained sensory

panel and demonstrated the relationship of sweetness and sourness to the chemical composition of the peppers. However, the flavor attributes identified for bell peppers (sweetness, sourness, bitterness, sharpness, grassy, cucumber, floral, green bell pepper aroma, and red bell pepper aroma) were not defined, which limits the universal use of those terms without further understanding the perception they describe. For example, the term 'sharpness' could be interpreted as a pungent (penetrating feeling) or a spicy flavor, which are two completely different perceptions. Similarly, the aroma and flavor of Peruvian chile peppers were evaluated using 10 attributes including acid, bell pepper, sweet, tomato, apple, citrus, herbal, fruity, oregano, and passion fruit (Patel et al., 2016), but with no reported definitions. Eggink et al. (2012) characterized the flavor and texture of different cultivars of sweet peppers and explained the variation in attribute intensities in relation to volatile, non-volatile compositions, and dry matter content of the peppers. In both studies, the sensory attributes were not defined, limiting the adoption of these as criteria for quality evaluation. Jimenez-Garcia et al. (2018) studied the effects of growth elicitors (hydrogen peroxide and salicylic acid) that improve disease resistance of plants on the sensory quality of sweet peppers. Although the authors recognized the need for a standardized lexicon and used the Quantitative Descriptive Analysis (QDA) method to train panelists, the attributes in the lexicon were not clearly defined and references were not published. More recently, Yang, Chambers, & Wang (2021) developed a lexicon to characterize the flavor of a specific variety of peppers, known as Sichuan peppers (*Zanthoxylum sp.*), that is extensively used in Chinese cuisine. However, as Sichuan pepper is not closely related to the more popularly consumed *Capsicum* family, some sensory characteristics are quite different and not completely extendible to other pepper varieties. On the other hand, Guzmán & Bosland (2017) focused on characterizing the nature, temporalities, and intensities of trigeminal heat sensations of hot peppers. This study also

helped in describing the rate of onset, location of heat perception in the mouth, and nature of heat perception (sharp or flat). However, the scoring of the heat attributes was done based on word choices rather than quantitative intensity scores. Moreover, the above-mentioned studies have focused more on the flavor, and to a lesser extent on the textural characteristics. Members of the *Capsicum* family being highly prone to postharvest water loss (Lownds, Banaras, & Bosland, 1994), undergo loss of cell turgor and consequently their firm texture. Previous studies on preserved pepper products such as those of banana peppers (Lee & Howard, 1999), jalapeno peppers (Howard, Burma, & Wagner, 1994; Saldana & Meyer, 1981), cherry peppers (Fleming et al., 1993), and red bell peppers (Koskiniemi, Truong, McFeeters, & Simunovic, 2013; McFeeters, Barrangou, Barish, & Morrison, 2004; Papageorge et al., 2003) have also reported texture loss after thermal processing and during storage, due to heat and oxygen exposure, and possible pectinolytic activity. This highlights the necessity of including texture as part of the sensory quality determination of peppers. Thus, this study aims to develop a sensory lexicon for fresh and preserved peppers that can guide future work on pepper quality improvement.

4.3. MATERIALS AND METHODS

4.3.1. Samples

Samples during training included various reference samples for attribute understanding. All reference samples were procured from local stores in Raleigh, NC. Chemicals including 2-isobutyl-3-methoxypyrazine (W313203, Sigma-Aldrich, MO, USA), geraniol (W250708, Sigma-Aldrich, MO, USA), and myrcene (W276200, Sigma-Aldrich, MO, USA) were procured as food grade. Seven fresh peppers (green, yellow, orange, and red bell peppers, banana peppers, jalapeno peppers, and pasilla peppers) and nine commercially available preserved peppers (including different brands of roasted red bell peppers, canned poblano peppers, acidified banana

peppers, acidified jalapeno peppers, brined piquante peppers, and bell peppers) were procured from local and online vendors for panel training and lexicon development. Following the development of the lexicon, a set of 22 fresh and preserved products of sweet and mildly hot peppers such as bell peppers, banana peppers, jalapeno peppers, piquant peppers, piquillo peppers, pepperoncinis, and sweet Peruvian peppers (Table 4.1), were evaluated by the trained panel to validate the lexicon. Care was taken to ensure that the samples for lexicon validation were procured from the same lot. Fresh samples were procured 1-3 days before a session, while shelf stable preserved pepper samples were procured up to two weeks in advance and stored under refrigeration to minimize any temperature-induced changes.

4.3.2. Panelist recruitment, screening, and training

Ten panelists were recruited from the North Carolina State University campus community based on availability and expressed interest. Screening procedures were implemented to include only those without food allergies, smoking habits, and any abnormalities in the five senses. Following satisfactory performance in basic taste identification, odor recognition, and difference tests, the ten panelists were trained for 37 hours (over a span of 5 months) in describing fresh and preserved pepper samples, understanding attribute definitions, use of the 0-15 point intensity scale, discriminating among attribute perceptions, and scoring intensities. A QDA method (Stone, Sidel, Oliver, Woolsey, & Singleton, 2004) was used, and training on the attributes was facilitated using reference samples with established intensities. An open-ended line scale labelled with numbers from 0 to 15 was used which was anchored with words (e.g., none, slight, moderate, high, extreme) and reference sample intensities. All data collection was carried out using online ballots designed using Compusense Cloud version 22 (Compusense Inc., Guelph, Ontario, Canada). Ballots had an option for panelists to review the definitions and

techniques of evaluations during practice sessions. Samples were served in 2 oz or 4 oz souffle cups monadically, along with purified drinking water, unsalted crackers, half & half, and muenster cheese as palate cleansers. Roasted coffee beans were also provided to panelists to cleanse their nasal passages. Nose clips were provided during the training phase for facilitating the understanding of flavor definitions.

Following training with numerous reference samples, three products that covered all attributes of the lexicon were chosen to serve as calibration references for the practice and evaluation phases. These calibration references included fresh red bell pepper (with a bright red color), roasted red bell peppers (brand MZ), and acidified banana peppers rings (brand ML) that were also part of the products evaluated for lexicon validation (Table 4.1). Scores for all attributes of the calibration references were assigned based on previous panel means and sensory evaluation by the panel leader in consultation with two trained descriptive sensory analysis panelists, each with more than 150 hours of training and experience. Practice sessions with a partial or complete lexicon were held to monitor panel performance and identify training needs. Practice was provided to the panel with three samples along with blinded calibration reference samples were served monadically with the serving order completely randomized. Such practice was replicated over three different sessions to determine accuracy, reliability, discrimination ability of the panel, and ultimately the readiness of the panel to evaluate samples for lexicon validation.

Panels were held virtually with panelists seated in separate rooms as a precautionary measure due to the ongoing pandemic. Panelists consented in writing before participating in the study in compliance with IRB protocol # 20822.

4.3.3. Development Of Terminology

During the training phase, panelists were asked to generate as many descriptors as possible for the various fresh and preserved pepper products provided to them. Closely matching sensory terminology were identified along with definitions and references from previously published literature to generate attributes from the descriptors generated by the panel. For those descriptors for which established sensory terms could not be found, definitions and references were developed. Feedback was sought from the panel for any necessary modifications on the newly developed definitions and references. The terminology was drafted in the form of a lexicon consisting of attribute terms, definitions, technique of evaluation, and references. This lexicon was used as a common guide during practice and evaluation phases to ensure that all panelists used a standardized evaluation protocol. At all times, the different sensory modalities were evaluated in the order: aroma, flavor, chemical feeling factors, and finally texture, to minimize fatigue-related errors in evaluation.

4.3.4. Validation of developed lexicon

A set of 22 assorted fresh and preserved pepper products were evaluated by the panel (Table 4.1). The objective was to determine the applicability and discrimination capacity of the lexicon with a wide variety of pepper products. All products were evaluated in duplicate by the panel. An incomplete block design was implemented by presenting 4 samples per session, for a total of 11 sessions held over 3 weeks.

4.3.5. Data Analysis

A two-way ANOVA with product, panelist, and the interaction as fixed effects was used to determine panel readiness for sample evaluations. A significant product effect indicated the

panel's discrimination ability, while significant product*panelist interactions meant lack of agreement among panelists on certain attribute intensities. Standard deviations associated with replications were used as indicators of individual panelists' and panel reliability. A standard deviation of < 2 for at least 90% of the attributes was set as the benchmark.

Mixed model ANOVA with product as fixed effect, and panelists as random effect was used to verify panel performance during sample evaluations for lexicon validation. The Restricted Maximum Likelihood (REML) method was used to fit the mixed model. Principle component analysis was carried out to visualize the discrimination among the various samples based on the overall sensory profiles. Correlations among attributes were analyzed to identify redundancies. All statistical analysis was carried out using JMP Pro 15.2.0 (SAS Institute Inc., Cary, NC, USA).

4.4. RESULTS AND DISCUSSION

4.4.1 Lexicon Development

A lexicon composed of 45 unique attributes to characterize fresh and preserved peppers was developed (Figure 4.1). The definitions, technique of evaluation, and references for each term are detailed in Table 4.2. This lexicon comprised 14 aroma, 19 flavor, 4 chemesthetic, and 8 textural attributes. It was developed by adapting relevant terminology and definitions from previously published literature that were equivalent in meaning to the descriptors generated by the panel. Certain attributes whose definitions were not well established in the literature or were unique to the samples used in this study, such as 'bell pepper', 'floral', 'fruity', 'tongue and throat burn', 'heat', 'slipperiness', and 'fracturability' were defined and relevant references were established. The insights for referencing 'bell pepper' and 'floral' attributes were drawn from the flavor chemistry of bell peppers studied by Luning et al., (1994) and Luning et al., (1995).

Definitions, techniques of evaluation, and reference intensities were modified based on panel feedback in a way to standardize the evaluation across all panelists, maximize scale usage, and assign accurate scores for the perceived intensities. Although some of the attributes in this lexicon were oftentimes present in low intensities, these could potentially indicate level of ripeness (e.g., sweetness, green) and possible fungal infestation (e.g., earthy) (Rousseaux, Diguta, Radoï-Matei, Alexandre, & Guilloux-Bénatier, 2014).

Aroma and flavor characteristics such as 'floral', 'green', and 'bell pepper' have been previously used as criteria for sensory evaluation of fresh bell peppers (Luning et al., 1994). Sensory testing of Peruvian peppers used 'tomato' as an attribute for evaluation (Patel et al., 2016), but its similarity to the 'cooked tomato' attribute established in the current work is uncertain due to a lack of published definitions in the former study. Similarly, the relation of 'sweet aroma' evaluated in *Capsicum chinense* hybrids to 'sweet aromatics' attribute in the current lexicon is likely but cannot be fully verified for the same reason. Basic tastes such as sweetness, sourness, and bitterness have been commonly evaluated across different types of peppers in previous studies (Eggink, 2013; Luning et al., 1994; Martinez et al., 2021; Patel et al., 2016). Also, floral, sweet aromatics, woody, bitter, umami, earthy, fruity, green, astringency, and pungency attributes coincided with the lexicon developed for Sichuan peppers (Yang et al., 2021). While numbing/anaesthetic was a chemesthetic character of Sichuan peppers, such an attribute was not perceived in the current study as it investigated the characteristics of milder peppers. Tongue tingle was yet another attribute found in Sichuan peppers which was not found in the peppers used in the current study. The chemesthetic perceptions in the current study manifested by the capsaicinoid contents were rather described as heat, and tongue and throat burn. Texture attributes such as juiciness, crunchiness (Martinez et al., 2021), and crispness

(Eggink, 2013) have been used in previous studies, but their equivalence to the definitions developed in the current study is uncertain due to lack of clear definitions in prior work. Numerous other attributes identified in the current study such as slipperiness, fibrousness, metallic, vinegar, smoky, burnt, fracturability, and skin awareness have not been used as criteria for evaluation of peppers and its products in previous work, and the attributes identified in past studies could not be reproduced due to lack of clear definitions. Thus, the current lexicon is a comprehensive, standardized tool for characterizing the aroma, flavor, and texture of fresh and preserved peppers. The lexicon developed in the current study has clear definitions of sensory attributes and reference materials that facilitate reproduction of this lexicon with other sensory panels in the future.

4.4.2. Lexicon Validation

The developed lexicon enabled the characterization of a wide variety of 22 commercially available fresh and preserved peppers with diverse sensory profiles. The results of the mixed model ANOVA are summarized in Tables 4.3, 4.4, and 4.5, which revealed the ability of the lexicon and panel to identify differences among the products ($p < 0.05$) The high discrimination power and reliability (low panelist variance) can also be noted about the panel's performance from these tables.

The principle component biplot (Figure 4.2) depicts the first two principle components explaining 71.4% of the total variation. All 45 attributes were required to describe the variation in sensory profiles of fresh and preserved peppers, indicated by significant differences among products ($p < 0.05$) for every attribute. The first principle component distinguished among peppers based on cooked characteristics. Roasted peppers loaded high on cooked flavors and were characterized by dominant cooked vegetable, cooked tomato, smoky, and burnt, umami and

bitter tastes, and metallic off-flavor. It was also interesting to note that two texture attributes i.e., slipperiness and fibrousness played an important role in differentiating such products (Figure 4.3). On the other hand, fresh, sweet-brined and acidified peppers loaded higher on fresh-like characteristics, notably conferred by texture attributes such as crispness, fracturability, hardness, crunchiness, and skin awareness. Other fresh-like characteristics included green, fruity, bell pepper, and floral attributes in fresh peppers, sweet and sweet aromatics in sweet-brined pepper products, and spicy, vinegar, pungent, TTB, and heat in acidified peppers. The metallic flavor was not only perceived in canned pepper products, but also in pasteurized roasted peppers sold in glass jars (products 12 and 16). However, the panel means for metallic flavor in fresh, sweet-brined and acidified peppers were low. This indicates that metallic flavor could possibly be a product of the red pepper roasting process, as seen in sun-dried peppers (Jun, Cho, Choi, & Kim, 2005) due to the formation of 2-pentylfuran possibly due to fatty acid oxidation (Buttery et al., 1969) by a combination of heat and light.

The second principle component discriminated fresh peppers from those preserved by acidification. Acidified products of banana pepper, pepperoncini, and jalapeno loaded high on vinegar aroma and flavor, sourness, astringency, and pungency. On the other hand, fresh bell peppers, jalapeno and banana peppers occupied the opposite side of the plot that loaded high on green, floral, and bell pepper aromas and flavors, sweet taste, and crisp and fracturing textures. Spicy flavor, heat, and tongue and throat burn attributes helped in characterizing further differences among the relatively hotter peppers such as jalapeno and banana peppers as depicted by the PCA biplot generated for aroma, flavor, and chemical feeling factors in Figure 4.3. Additionally, differentiation among subcategories of pepper products (name the subcategories here) was also enabled by the lexicon (Figures 4.4, 4.5, 4.6, and 4.7). The biplots explained

81.5%, 83.6%, 68.6%, and 76.4% of the total variation respectively. Among fresh peppers, jalapenos and green bell peppers were high on green aroma and flavor, and hard and crunchy texture, while the other colored bell peppers were characterized by fruity, sweet, juicy, floral, and bell pepper attributes. Among the sweet-brined pepper products, the piquante peppers were high on sweet, fruity, and sweet aromatic notes, while the cherry peppers were relatively low on those. Within the acidified peppers category, some of the banana peppers were mostly pungent and spicy along with heat and TTB attributes predominating, while other banana pepper products were characterized as fruity, sweet aromatic, crunchy, and crispy. The lexicon was useful in identifying off-flavors such as metallic in canned roasted red bell peppers, which also indicates its usefulness in differentiating products based on the methods of manufacture. Tables 4.2 to 4.9 detail the product means for all the 45 attributes and indicate statistical differences among them.

A correlational matrix which is depicted as a heat map in Figure 4.8 shows high correlation coefficients only among those attributes which occur most often together in products but have definitions with completely different meanings. For example, vinegar, spicy, pungency, astringency, and sourness were found highly correlated, but their definitions are fundamentally different, using different senses to perceive each of these. Thus, all 45 attributes were found to be unique and non-redundant. However, feedback from the panel suggested that an attribute quantifying the amount of seeds in products was missing from the lexicon to characterize and differentiate pepper products on their entirety. Thus, ‘seed awareness’ was defined along with reference anchors and added to the lexicon as a texture attribute. Thus, a sensory lexicon with 46 attributes was developed, which provides a major portion of the attributes necessary to evaluate the sensory quality of a wide variety of fresh and processed peppers.

4.5. CONCLUSION

The lexicon developed in the current study provides an extensive vocabulary for evaluating the quality of both fresh and preserved pepper products, which is the first of its kind. The lexicon was validated and found to be discriminative among a wide variety of products, with 46 unique sensory attributes playing a significant role in characterizing the quality of fresh and preserved peppers. Provision of clear definitions and reference intensities make this lexicon reproducible for future work. Besides the foreseen wide applicability of this lexicon, the intended benefits to breeders of fresh peppers and manufacturers of preserved peppers are certain, by serving as an invaluable tool for quality monitoring and improvement

TABLES

Table 4.1. Samples used for lexicon validation.

Product number	**Botanical name**	**Common name**	**Brand**	**Additional details (packaging & special designations)**
Fresh peppers (F)				
1	*Capsicum annuum* 'Grossum'	Green bell pepper	n/a	
2	*Capsicum annuum* 'Grossum'	Yellow bell pepper	n/a	
3	*Capsicum annuum* 'Grossum'	Orange bell pepper	n/a	
4	*Capsicum annuum* 'Grossum'	Red bell pepper	n/a	
5	*Capsicum annuum* 'Banana pepper'	Banana peppers	n/a	
6	*Capsicum annuum* 'Jalapeño'	Jalapeno peppers	n/a	
Sweet acidified pepper products (S)				
7	*Capsicum annuum* 'Grossum'	Red bell peppers	DS	Polyethylene Terephthalate jar
8	*Capsicum baccatum*	Piquante peppers (Native to South Africa)	PP	Glass jar
9	*Capsicum annum* var. Crerasiforme	Cherry peppers	MZ	Glass jar
10	*Capsicum baccatum*	Peruvian peppers	DL	Glass jar
Acidified pepper products (A)				
11	*Capsicum annuum* 'Grossum'	Green bell peppers	SD	Glass jar
12	*Capsicum annuum* 'Frigitello'	Pepperoncini	ML	Glass jar
13	*Capsicum annuum* 'Frigitello'	Pepperoncini	MZ	Glass jar; Greek-style
14	*Capsicum annuum* 'Banana pepper'	Banana peppers	MZ	Glass jar
15	*Capsicum annuum* 'Banana pepper'	Banana peppers	BV	Glass jar

Table 4.1 (continued). Samples used for lexicon validation.

16	*Capsicum annuum* 'Banana pepper'	Banana peppers	ML	Glass jar
17	*Capsicum annuum* 'Jalapeño'	Jalapeño peppers	LC	Glass jar
18	*Capsicum annuum* 'Jalapeño'	Jalapeño peppers	MZ	Glass jar; tamed jalapeños
Roasted pepper products (R)				
19	*Capsicum annuum*	Piquillo peppers (Native to Spain)	HT	Metal can
20	*Capsicum annuum* 'Grossum'	Red bell peppers	CT	Glass jar
21	*Capsicum annuum* 'Grossum'	Red bell peppers	MZ	Glass jar
22	*Capsicum annuum* 'Grossum'	Red bell peppers	FM	Metal can

Table 4.2. Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

Attribute	Definition	Technique	References and intensities
Aroma			
Vinegar	The characteristic aromatics associated with vinegar or acetic acid[a*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one to two brief whiffs. Close the lid and score the intensity of 'vinegar' aroma.	[d]None-slight: 0.1% acetic acid solution = 2 Moderate: 0.7% acetic acid solution = 7 Extreme: 1.3% acetic acid solution = 15
Burnt	The dark brown carbon impression of charred or scorched food, characterized by sharp, acrid aromatics[b,c*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one to two brief whiffs. Close the lid and score the intensity of 'burnt' aroma.	None-slight: Arrowhead Mills puffed wheat = 2 High-extreme: Burnt toast = 12 *Toast Wonderbread classic slice bread at highest setting (6) on an Oster electric toaster for a full toast*

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			cycle. Cut into 1-inch squares while still warm and add 3 x squares to 4 oz souffle cups and close with lids immediately. Allow to cool.
Smoky	An acute aromatic that is characteristic of the products of combustion of wood or leaves[e*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one to two brief whiffs. Close the lid and score the intensity of 'smoky' aroma.	[c*]Slight: Colgin Mesquite liquid smoke in water (2 drops/300 ml) = 4 Moderate-high: Colgin Mesquite liquid smoke in water (2 drops/40 ml) = 8.5
Bell pepper	A vegetal aromatic that is characteristic of fresh bell pepper.	Open lid only about a 1/2 of an inch on one side of sample vial and sniff in one or two brief whiffs. Evaluate the intensity of 'bell pepper' aroma.	Slight-moderate: 2-isobutyl-3-methoxypyrazine in water @ 0.01 uL/L = 5 Moderate: 2-isobutyl-3-methoxypyrazine in water @ 0.03 uL/L = 7

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			High-extreme: 2-isobutyl-3-methoxypyrazine in water @ 0.1 uL/L = 12
Floral	Aromatics characteristic of flowers, specifically similar to geranium, elderflower, and/or violet, singly or in combination.	Open lid only about a 1/2 of an inch on one side of sample vial and sniff in one or two brief whiffs. Evaluate the intensity of 'floral' aroma.	Moderate: Geraniol and myrcene in water @ 5 uL/L and 0.5 uL/L respectively = 7
Fruity	The aromatics generally associated with fruits that may include tropical, and/or stone fruits, apples, and red berries.	Open lid only about a 1/2 of an inch on one side of sample container and sniff in one or two brief whiffs. Evaluate the intensity of 'fruity' aroma.	Slight: Fruit juice blend in water (1:3) = 4 Moderate: Fruit juice blend in water (1:1) = 8 High-extreme: Fruit juice blend = 12 *Fruit juice blend was prepared by*

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			combining Harris Teeter Pineapple Juice (100% juice, no added sugar), Simply Apple juice (Not from concentrate), Simply Peach juice (Not from concentrate) each @ 4.5% and Tropicana Summer Berry Bliss @ 1.5% in water.
Spicy	"Hot" aroma characteristic of chili peppers, particularly in relation to the aromatic perception of capsaicinoids.	Open lid only about a 1/2 of an inch on one side of sample container and sniff in one or two brief whiffs. Evaluate the intensity of 'spicy' aroma.	Moderate: Mt Olive mild banana pepper rings = 7

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

Woody	The aromatics associated with the bark of a tree or dry cut wood[f,g*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one to two brief whiffs. Close the lid and score the intensity of 'woody' aroma.	[e*]Slight: Diamond shelled walnuts = 4 Extreme: Hickory wood chips = 15
Green	The aromatics associated with cut grass, green plant-based materials, or under-ripe fruits[e,f,g,h,i,j*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one to two brief whiffs. Close the lid and score the intensity of 'green' aroma.	[e,f,g,h,i*]Moderate-high: Parsley water = 9 *25 g chopped fresh parsley soaked in 300 ml distilled water at room temperature for 15 min, filtered and diluted with distilled water in 1:1 ratio.*
Earthy	Humus-like aromatics such as damp soil, decaying vegetation or	Open lid only about a ½ of an inch on one side of the sample container and sniff in one to two brief whiffs. Close the lid and score the intensity of 'earthy' aroma.	[c,f,h,l*]None-slight: Frozen baby lima beans (thawed) = 3 Moderate-high: Raw mushroom (1/2" slices) = 9

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

	cellar-like characteristics[h,k*].		
Cooked tomato	The vegetal aromatics associated with cooked tomato, such as thermally processed tomato juice, sauce, or pastes[m*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one or two brief whiffs. Evaluate the intensity of 'cooked tomato' aroma.	None-slight: Campbell's tomato juice in water (1:7) = 3 Slight-moderate: Campbell's tomato juice in water (1:3) = 6 High-extreme: Campbell's tomato juice in water (1:1) = 12
Cooked vegetable	A general term to describe a combination of cooked vegetable aromas that may include cooked celery, carrot, corn, potato, or other vegetables[l].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one or two brief whiffs. Evaluate the intensity of 'cooked vegetable' aroma.	Slight: Vegetable stock in water (1:3) = 4 Moderate: Vegetable stock in water (1:7) = 8 High-extreme: Vegetable stock in water (1:15) = 12 *Kitchen Basics vegetable stock*

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			(unsalted) diluted with water at different proportions.
Sweet aromatics	Aromatics associated with the impression of sweet substances such as cooked sugar, caramel, or candy[f*].	Open lid only about a 1/2 of an inch on one side of the sample container and sniff in one or two brief whiffs. Evaluate the intensity of 'sweet aromatics'.	Slight-moderate: Maltol in water (200 ppm) = 5
Flavor			
Vinegar	The characteristic aromatics associated with vinegar or acetic acid[a*].	Place sample in mouth and chew normally. Expectorate, inhale, and score the intensity of 'vinegar' flavor.	[d]None-slight: 0.1% acetic acid solution = 2 Moderate: 0.7% acetic acid solution = 7 Extreme: 1.3% acetic acid solution = 15

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

Burnt	The dark brown carbon impression of charred or scorched food, characterized by sharp, acrid aromatics[b,c*].	Place sample in mouth and chew normally. Score the intensity of 'burnt' flavor.	Slight-moderate: Arrowhead Mills puffed wheat = 5 High-extreme: Burnt toast = 12 (a)
Smoky	An acute aromatic that is a product of combustion of wood or leaves[e*].	Place sample in mouth and chew normally. Score the intensity of 'smoky' flavor.	[c*]Slight: Colgin Mesquite liquid smoke in water (2 drops/300 ml) = 4 (a) Moderate-high: Colgin Mesquite liquid smoke in water (2 drops/40 ml) = 8.5 (a)
Bell pepper	A vegetal aromatic that is characteristic of fresh bell pepper.	Place sample in mouth and chew normally. Score the intensity of 'bell pepper' flavor.	Slight-moderate: 2-isobutyl-3-methoxypyrazine in water @ 0.01 uL/L = 5 (a) Moderate: 2-isobutyl-3-

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			methoxypyrazine in water @ 0.03 uL/L = 7 (a) High: 2-isobutyl-3-methoxypyrazine in water @ 0.1 uL/L = 12 (a)
Floral	Aromatics characteristic of flowers, specifically similar to geranium, elderflower, and/or violet, singly or in combination.	Place sample in mouth and chew normally. Score the intensity of 'floral' flavor.	Moderate: Geraniol and myrcene in water @ 5 uL/L and 0.5 uL/L respectively = 7 (a)
Fruity	The aromatics generally associated with fruits that may include tropical, and/or stone fruits, apples, and red berries.	Place sample in mouth and chew normally. Score the intensity of 'fruity' flavor.	None-slight: Fruit juice blend in water (1:3) = 2 Slight-moderate: Fruit juice blend in water (1:1) = 5 Moderate-high: Fruit juice blend = 10

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			Fruit juice blend was prepared by combining Harris Teeter Pineapple Juice (100% juice, no added sugar), Simply Apple juice (Not from concentrate), Simply Peach juice (Not from concentrate) each @ 4.5% and Tropicana Summer Berry Bliss @ 1.5% in water.
Spicy	"Hot" aroma characteristic of chilli peppers, particularly in relation to the aromatic perception of capsaicinoids.	Place sample in mouth and chew normally. Expectorate, inhale, and score the intensity of 'spicy' flavor.	Slight-moderate: Mt Olive mild banana pepper rings = 5

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

Woody	The aromatics associated with the bark of a tree or dry cut wood[f,g*].	Place sample in mouth and chew normally. Score the intensity of 'woody' flavor.	[e*]Slight: Diamond shelled walnuts = 4 Extreme: Wood chips = 15 (a)
Green	The aromatics associated with cut grass, green plant-based materials, or under-ripe fruits[e,f,g,h,i,j*].	Place sample in mouth and chew normally. Score the intensity of 'green' flavor.	[e,f,g,h,i*]Slight-moderate: Parsley water = 6 25 g chopped fresh parsley soaked in 300 ml distilled water at room temperature for 15 min, filtered and diluted with distilled water in 1:1 ratio.
Earthy	Humus-like aromatics associated with damp soil, decaying vegetation or cellar-like characteristics[h,k*].	Place sample in mouth and chew normally. Score the intensity of 'earthy' flavor.	[c,f,h,l*]Slight: Frozen baby lima beans (thawed) = 3 Moderate: Raw mushroom (1/2" slices) = 9

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

Cooked tomato	The vegetal aromatics associated with cooked tomato, such as thermally processed tomato juice, sauce, or pastes[m*].	Place sample in mouth and chew normally. Score the intensity of 'cooked tomato' flavor.	Slight: Campbell's tomato juice in water (1:7) = 3 Moderate: Campbell's tomato juice in water (1:3) = 8 High: Campbell's tomato juice in water (1:1) = 12
Cooked vegetable	A general term to describe a combination of cooked vegetable aromas that may include cooked celery, carrot, corn, potato, or other vegetables[l].	Place sample in mouth and chew normally. Expectorate, inhale, and score the intensity of 'cooked vegetable' flavor.	Slight: Vegetable stock in water (1:3) = 4 Moderate: Vegetable stock in water (1:7) = 8 High: Vegetable stock in water (1:15) = 12 *Kitchen Basics vegetable stock (unsalted) was used.*

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

Sweet aromatics	Aromatics associated with the impression of sweet substances such as cooked sugar, caramel, or candy[f*].	Place sample in mouth and chew normally. Expectorate, inhale, and score the intensity of 'sweet aromatics'.	Slight-moderate: Maltol in water (200 ppm) = 5
Metallic	Aromatics associated with "tin" cans, iron, copper, or oxidized silver[c,l*].	Place sample in mouth and chew normally. Expectorate, inhale, and score the intensity of 'metallic' flavor.	[n*]Slight: Ferrous sulfate in water @ 1ppm = 4 Moderate: Ferrous sulfate in water @ 2ppm = 8 High: Ferrous sulfate in water @ 3ppm = 12
Basic tastes			
Sweet	Taste perceived on the tongue stimulated by	Place sample in mouth and chew normally. Score the intensity of 'sweet' taste.	[o]None-slight: 2% sucrose solution = 2 Slight-moderate: 5% sucrose solution

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

	sucrose and other sugars[o].		= 5 Moderate-high: 10% sucrose solution = 10
Salty	Taste perceived on the tongue stimulated by salts, mainly sodium chloride and to a lesser degree by others such as potassium chloride[o].	Place sample in mouth and chew normally. Score the intensity of 'salty' taste.	[o]Slight-moderate: 0.35% sodium chloride solution = 5 Moderate: 0.434% sodium chloride solution = 7 Moderate-high: 0.55% sodium chloride solution = 10
Sour	Taste perceived on the tongue stimulated by acids, such as citric, malic, or lactic acid[o].	Place sample in mouth and chew normally. Score the intensity of 'sour' taste.	[o]Slight-moderate: 0.08% citric acid solution = 5 Moderate: 0.108% citric acid solution = 7

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			Moderate-high: 0.15% citric acid solution = 10
Bitter	Taste perceived on tongue stimulated by substances such as quinine, caffeine, hop bitters[o].	Place sample in mouth and chew normally. Score the intensity of 'bitter' taste.	[o]None-slight: 0.02% caffeine solution = 2 Slight-moderate: 0.08% caffeine solution = 5
Umami	Savory, and somewhat flat, brothy taste perceived on tongue associated with juices from cooked meat and stimulated by substances	Place sample in mouth and chew normally. Score the intensity of 'umami' taste.	[p]None-slight: 0.1% monosodium glutamate solution = 2 Slight-moderate: 0.3% monosodium glutamate solution = 5

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

	such as monosodium glutamate[f,l*].		
Chemical feeling factors			
Astringency	Shrinking, puckering, drying, or roughing of the tongue or other tissues of the mouth by substances such as alum or tannins[a].	Place sample in mouth and chew normally. Expectorate, swallow any residual sample, wait for 5 seconds, and then evaluate the intensity of 'astringent' mouthfeel.	[d]None-slight: 0.025% alum in water = 2 Slight-moderate: 0.055% alum in water = 5 Moderate-high: 0.11% alum in water = 10
Pungency	The sharp physically penetrating sensation in the nasal cavity[f*].	Orthonasal: Open lid only about a ½ of an inch on one side of the sample container and sniff in one to two brief whiffs. Evaluate the intensity of 'pungent' sensation.	Slight-moderate: S&B Japanese horseradish in water (0.2%) = 5 (a) Moderate-high: S&B Japanese horseradish in water (0.5%) = 10 (a)

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

		Retronasal: Place sample in mouth and chew normally. Expectorate and evaluate the intensity of 'pungent' sensation.	Extreme: S&B Japanese horseradish in water (1%) = 15 (a)
Tongue and throat burn (TTB)	The chemical feeling factor described as a burning sensation perceived in the throat and/or on the tongue[n,q*].	Place sample in mouth and chew normally. Expectorate, swallow any residual sample, then evaluate the intensity of 'tongue and throat burn'.	Slight-moderate: Tabasco sauce in water @ 1% = 6 Moderate-high: Tabasco sauce in water @ 1.5% = 12
Heat	The sensation of warmth in the mouth, attributed to the perception of capsaicinoids.	Place sample in mouth and chew normally. Swallow or expectorate sample, wait for 10 seconds, and then score the intensity of 'heat' felt in the mouth.	Slight-moderate: Tabasco sauce in water @ 1% = 5 Moderate-high: Tabasco sauce in water @ 1.5% = 10
Texture			
Slipperiness	The extent to which the	Place sample in mouth and move back and	Moderate-high: Green Giant retorted

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

	sample slides easily across the tongue and oral surfaces.	forth across palate using the tongue. Evaluate the degree to which the sample slides easily between the oral surfaces.	mushroom slices = 10
Hardness	The force required to compress the sample between the molars[r].	Place food between the molars and bite down slowly, evaluating the force required to compress the food. Evaluate the force required to compress the sample without breaking it.	[o,r*]Slight: Muenster cheese (1/2") = 4 Moderate: Hebrew National frankfurter (1/2") = 7 High: Carrots (1/2") = 11
Crispness	The multiple, higher pitched sounds produced as the sample is crushed slowly with the molar teeth[r].	Place sample between molars and compress sample slowly. Repeat compression 3 times with the same sample. Score the intensity and frequency of higher-pitched sounds.	Slight: Gala apples (1/2") = 4 High: Water chestnut (1/2 slices) = 12
Fracturability	The ability of the sample to break into distinct	Place sample between the molar and bite down quickly.	None-slight: Texas Toast Bread (1/2") = 1

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

	pieces (fracture) rather than deform.		Moderate: Hard-boiled egg white = 7 High: Jicama (1/2") = 12
Crunchiness	A singular lower-pitched noise produced with each chew[r].	Place sample between back molars and bite down quickly. Score the intensity of lower-pitched sounds in first 3-5 chews.	[r]Slight: Planters peanuts = 4 High: Carrots (1/2") = 12
Juiciness	Amount of juice released from the sample during mastication[o*, r]	Place sample between the back molar teeth and begin the mastication process. Score the intensity based on the amount of moisture released from the sample. Juiciness should be evaluated in the first 3-5 chews.	[o]Slight: Raw mushroom (1/2") = 4 Extreme: Watermelon (1/2") = 15
Seed awareness	The degree to which seeds are perceived in the mouth.	Place sample between molars and begin masticating for 3-5 chews. Use tongue and/or oral surfaces to evaluate the degree of seeds perceived.	[k*]Slight: 1 g sesame seeds in 45 g Hunt's tomato sauce = 4 Moderate: 1 g sesame seeds in 30 g Hunt's tomato sauce = 8

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			High: 1 g sesame seeds in 15 g Hunt's tomato sauce = 12
Skin awareness	The degree to which the outside layer of the product is perceived as intact pieces during mastication[r].	Place sample between molars and begin the mastication process. Chew the sample 3-5 times and score the degree of intactness of the peel by feeling it with the tongue.	[r]Moderate-high: Red seedless grapes = 10
Fibrousness	The degree to which fibers (thread or filament-like structures) are perceived in the sample[k,l*].	Place sample in mouth and chew normally for five to eight chews. Use tongue to evaluate the sample mass, and score the intensity based on the amount of distinct fibers (strands) in the sample.	[s]Slight-moderate: Cooked strawberries = 5 *Frozen strawberries of 230g were cooked in a microwave at power 6 for 2 ½ minutes.*

Table 4.2 (continued). Attributes, definitions, technique of evaluation, and references for characterizing the sensory properties of fresh and preserved peppers.

			Moderate-high: Dole canned pineapple (1/2") = 10

*Superscript letters indicate the literature reference from which the information has been taken directly or modified (marked with *).*

[a]Johanningsmeier, Thompson, & Fleming (2003), [b]Lotong, Iv, & Chambers (2000), [c]Jaffe, Wang, & Chambers (2017), [d]Da Conceicao Neta, Johanningsmeier, Drake, & McFeeters (2007), [e]Chambers et al. (2016), [f]Talavera-Bianchi, Chambers IV, & Chambers (2010), [g]Chun, Chambers, & Han (2020), [h]Godoy, Chambers, & Yang (2020), [i]Yang et al., (2021), [j]Suwonsichon, Chambers IV, Kongpensook, & Oupadissakoon (2012), [k]Hongsoongnern & Chambers (2008), [l]Sharma et al. (2020), [m] Lawless, Hottenstein, & Ellingsworth (2012), [n]Koppel & Chambers (2010), [o]Meilgaard, Civille, & Carr (2016), [p]Martin, Maire, Chabanet, & Issanchou (2015), [q]Ledeker, Suwonsichon, Chambers, & Adhikari (2014), [r]Rosenberg (2013), [s]Rosales & Suwonsichon (2015)

Table 4.3. Mixed model summary for aroma attributes.

Attribute	**Fixed Effect**	**F Ratio**	**Prob > F**	**Random Effect**	**Variance Component**	**Std Error**	**95% Lower**	**95% Upper**	**Wald p-Value**	**% of total variance**
Vinegar	Product	39.52	<.0001							
				Panelist	1.07	0.66	-0.22	2.36	0.1033	18.67
				Product*Panelist	2.31	0.43	1.48	3.15	<.0001	40.33
				Residual	2.35	0.25	1.93	2.93		41.01
				Total	5.74	0.77	4.48	7.61		100.00
Burnt	Product	31.80	<.0001							
				Panelist	0.01	0.01	-0.01	0.04	0.3344	3.57

				Product*Panelist	0.18	0.03	0.12	0.24	<.0001	49.45
				Residual	0.17	0.02	0.14	0.21		46.97
				Total	0.36	0.03	0.30	0.44		100.00
Smoky	Product	59.93	<.0001							
				Panelist	0.02	0.03	-0.03	0.07	0.4008	2.41
				Product*Panelist	0.28	0.08	0.13	0.43	0.0002	30.59
				Residual	0.62	0.07	0.51	0.77		67.00
				Total	0.93	0.08	0.79	1.10		100.00
Bell pepper	Product	18.83	<.0001							
				Panelist	0.29	0.18	-0.07	0.64	0.1132	14.90
				Product*Panelist	0.63	0.14	0.36	0.91	<.0001	33.17
				Residual	0.99	0.11	0.82	1.24		51.94
				Total	1.91	0.23	1.54	2.45		100.00
Floral	Product	17.06	<.0001							
				Panelist	0.20	0.13	-0.06	0.46	0.1245	12.06
				Product*Panelist	0.46	0.13	0.21	0.70	0.0003	27.27

Table 4.3 (continued). Mixed model summary for aroma attributes.

				Residual	1.02	0.11	0.84	1.27		60.67
				Total	1.68	0.18	1.38	2.09		100.00
Fruity	Product	12.43	<.0001							
				Panelist	0.11	0.08	-0.06	0.27	0.2091	6.23
				Product*Panelist	0.67	0.14	0.39	0.95	<.0001	39.41
				Residual	0.92	0.10	0.76	1.15		54.36
				Total	1.70	0.16	1.43	2.06		100.00
Spicy	Product	18.96	<.0001							
				Panelist	0.68	0.43	-0.17	1.52	0.1157	14.31

				Product*Panelist	1.56	0.35	0.87	2.25	<.0001	32.99
				Residual	2.49	0.27	2.04	3.11		52.70
				Total	4.73	0.55	3.82	6.02		100.00
Woody	Product	4.96	<.0001							
				Panelist	0.41	0.23	-0.05	0.87	0.0831	27.53
				Product*Panelist	0.35	0.09	0.17	0.53	0.0001	23.58
				Residual	0.72	0.08	0.59	0.90		48.89
				Total	1.48	0.25	1.09	2.12		100.00
Green	Product	13.42	<.0001							
				Panelist	0.49	0.30	-0.10	1.08	0.1028	19.25
				Product*Panelist	1.10	0.19	0.72	1.47	<.0001	43.05
				Residual	0.96	0.10	0.79	1.20		37.70
				Total	2.54	0.35	1.97	3.40		100.00
Earthy	Product	3.85	<.0001							
				Panelist	0.26	0.15	-0.04	0.55	0.0933	21.50
				Product*Panelist	0.35	0.08	0.19	0.51	<.0001	29.76
				Residual	0.58	0.06	0.47	0.72		48.74

Table 4.3 (continued). Mixed model summary for aroma attributes.

				Total	1.19	0.17	0.91	1.61		100.00
Cooked tomato	Product	14.76	<.0001							
				Panelist	0.13	0.10	-0.06	0.32	0.1797	8.50
				Product*Panelist	0.84	0.13	0.58	1.10	<.0001	55.04
				Residual	0.55	0.06	0.45	0.69		36.46
				Total	1.52	0.16	1.25	1.89		100.00
Cooked vegetable	Product	17.76	<.0001							

				Panelist	0.29	0.19	-0.08	0.65	0.1268	11.51
				Product*Panelist	0.62	0.18	0.26	0.98	0.0008	25.03
				Residual	1.57	0.17	1.29	1.96		63.47
				Total	2.48	0.26	2.04	3.07		100.00
Sweet aromatics	Product	5.79	<.0001							
				Panelist	0.01	0.02	-0.03	0.06	0.5314	1.55
				Product*Panelist	0.32	0.08	0.17	0.48	<.0001	34.70
				Residual	0.59	0.06	0.49	0.74		63.75
				Total	0.93	0.08	0.79	1.11		100.00

Table 4.4. Mixed model summary for flavor attributes.

Attribute	Fixed Effect	F Ratio	Prob > F	Random Effect	Variance Component	Std Error	95% Lower	95% Upper	Wald p-Value	% of total variance
Aromatics										
Vinegar	Product	45.41	<.0001							
				Panelist	1.49	0.89	-0.25	3.23	0.0928	22.01
				Product*Panelist	2.12	0.46	1.21	3.03	<.0001	31.28
				Residual	3.17	0.34	2.60	3.95		46.72
				Total	6.78	0.99	5.19	9.24		100.00
Burnt	Product	43.63	<.0001							
				Panelist	0.02	0.02	-0.02	0.06	0.2557	4.90
				Product*Panelist	0.21	0.04	0.13	0.29	<.0001	42.84
				Residual	0.25	0.03	0.21	0.32		52.26
				Total	0.48	0.04	0.41	0.59		100.00
Smoky	Product	61.88	<.0001							
				Panelist	0.03	0.03	-0.03	0.09	0.2796	3.50
				Product*Panelist	0.14	0.07	0.00	0.29	0.0553	14.99
				Residual	0.77	0.08	0.63	0.96		81.51
				Total	0.94	0.08	0.81	1.12		100.00
Bell pepper	Product	20.52	<.0001							
				Panelist	0.49	0.30	-0.10	1.09	0.1042	16.83
				Product*Panelist	0.84	0.21	0.43	1.25	<.0001	28.63
				Residual	1.60	0.17	1.31	1.99		54.54
				Total	2.93	0.36	2.33	3.80		100.00
Floral	Product	15.31	<.0001							
				Panelist	0.14	0.10	-0.06	0.34	0.1583	8.69

Table 4.4 (continued). Mixed model summary for flavor attributes.

				Product*Panelist	0.54	0.13	0.28	0.79	<.0001	32.63
				Residual	0.97	0.10	0.79	1.21		58.68
				Total	1.65	0.16	1.38	2.02		100.00
Fruity	Product	7.77	<.0001							
				Panelist	0.07	0.06	-0.04	0.19	0.2095	5.94
				Product*Panelist	0.41	0.10	0.22	0.61	<.0001	33.26
				Residual	0.76	0.08	0.62	0.94		60.80
				Total	1.25	0.11	1.05	1.50		100.00
Spicy	Product	32.52	<.0001							
				Panelist	0.04	0.07	-0.11	0.19	0.5847	0.90
				Product*Panelist	-0.11	0.35	-0.79	0.57	0.7476	0.00
				Residual	4.51	0.48	3.70	5.62		99.10
				Total	4.55	0.49	3.73	5.68		100.00
Woody	Product	9.66	<.0001							
				Panelist	0.47	0.27	-0.05	0.99	0.0781	30.51
				Product*Panelist	0.21	0.09	0.04	0.38	0.018	13.45
				Residual	0.86	0.09	0.71	1.07		56.05
				Total	1.54	0.28	1.11	2.27		100.00
Green	Product	12.16	<.0001							
				Panelist	0.58	0.36	-0.12	1.29	0.1022	19.49
				Product*Panelist	1.29	0.22	0.85	1.73	<.0001	43.15
				Residual	1.12	0.12	0.92	1.40		37.36
				Total	3.00	0.42	2.32	4.02		100.00
Earthy	Product	3.07	<.0001							
				Panelist	0.27	0.16	-0.04	0.59	0.09	21.85
				Product*Panelist	0.26	0.08	0.10	0.42	0.0012	21.12
				Residual	0.71	0.08	0.58	0.88		57.04

Table 4.4 (continued). Mixed model summary for flavor attributes.

				Total	1.24	0.18	0.96	1.68		100.00
Cooked tomato	Product	15.00	<.0001							
				Panelist	0.12	0.10	-0.07	0.32	0.2079	7.10
				Product*Panelist	1.00	0.16	0.70	1.31	<.0001	57.66
				Residual	0.61	0.07	0.50	0.77		35.24
				Total	1.74	0.18	1.44	2.15		100.00
Cooked vegetable	Product	16.75	<.0001							
				Panelist	0.31	0.19	-0.08	0.69	0.1168	13.80
				Product*Panelist	0.67	0.16	0.35	1.00	<.0001	30.46
				Residual	1.23	0.13	1.01	1.54		55.74
				Total	2.21	0.25	1.79	2.80		100.00
Sweet aromatics	Product	8.25	<.0001							
				Panelist	0.13	0.08	-0.03	0.29	0.1177	12.11
				Product*Panelist	0.17	0.08	0.02	0.32	0.0264	15.91
				Residual	0.78	0.08	0.64	0.97		71.98
				Total	1.08	0.11	0.89	1.34		100.00
Metallic	Product	3.60	<.0001							
				Panelist	0.03	0.03	-0.04	0.10	0.3642	2.57
				Product*Panelist	0.26	0.10	0.06	0.45	0.009	20.95
				Residual	0.95	0.10	0.78	1.18		76.49
				Total	1.24	0.10	1.06	1.47		100.00
Basic tastes										
Sweet	Product	15.01	<.0001							
				Panelist	0.07	0.06	-0.04	0.19	0.2171	4.23

Table 4.4 (continued). Mixed model summary for flavor attributes.

				Product*Panelist	-0.01	0.13	-0.26	0.25	0.963	0.00
				Residual	1.64	0.17	1.35	2.05		95.78
				Total	1.71	0.18	1.40	2.14		100.00
Salty	Product	15.92	<.0001							
				Panelist	0.52	0.33	-0.13	1.17	0.1197	13.27
				Product*Panelist	1.20	0.29	0.63	1.77	<.0001	30.86
				Residual	2.18	0.23	1.78	2.71		55.87
				Total	3.90	0.43	3.17	4.91		100.00
Sour	Product	38.32	<.0001							
				Panelist	1.29	0.77	-0.21	2.80	0.0923	22.45
				Product*Panelist	1.84	0.39	1.07	2.61	<.0001	32.01
				Residual	2.62	0.28	2.15	3.27		45.54
				Total	5.75	0.85	4.39	7.88		100.00
Bitter	Product	7.67	<.0001							
				Panelist	0.19	0.11	-0.03	0.41	0.0913	19.48
				Product*Panelist	0.11	0.06	-0.01	0.24	0.0733	11.66
				Residual	0.67	0.07	0.55	0.84		68.87
				Total	0.97	0.13	0.77	1.28		100.00
Umami	Product	15.33	<.0001							
				Panelist	0.07	0.04	-0.01	0.15	0.0948	17.43
				Product*Panelist	0.04	0.03	-0.01	0.09	0.1637	9.23
				Residual	0.28	0.03	0.23	0.35		73.34
				Total	0.38	0.05	0.31	0.50		100.00

Table 4.5. Mixed model summary for chemesthetic and texture attributes.

Attribute	Fixed Effect	F Ratio	Prob > F	Random Effect	Variance Component	Std Error	95% Lower	95% Upper	Wald p-Value	% of total variance
Chemical feeling factors										
Astringency	Product	19.33	<.0001							
				Panelist	0.05	0.04	-0.03	0.12	0.2271	4.33
				Product*Panelist	0.09	0.08	-0.08	0.25	0.2946	8.01
				Residual	0.95	0.10	0.78	1.19		87.66
				Total	1.09	0.09	0.93	1.29		100.00
Pungency (orthonasal)	Product	31.54	<.0001							
				Panelist	0.23	0.17	-0.09	0.56	0.1642	7.85
				Product*Panelist	0.78	0.23	0.33	1.22	0.0007	26.35
				Residual	1.94	0.21	1.59	2.41		65.80
				Total	2.94	0.28	2.47	3.57		100.00
Pungency (retronasal)	Product	23.60	<.0001							
				Panelist	0.41	0.25	-0.09	0.90	0.1073	13.55
				Product*Panelist	0.29	0.21	-0.12	0.70	0.1652	9.63
				Residual	2.30	0.25	1.89	2.87		76.82
				Total	3.00	0.32	2.46	3.75		100.00
Tongue and throat burn	Product	33.22	<.0001							
				Panelist	0.45	0.29	-0.13	1.03	0.1279	8.40
				Product*Panelist	-0.20	0.37	-0.92	0.53	0.5938	0.00
				Residual	4.90	0.52	4.01	6.10		91.60
				Total	5.34	0.60	4.34	6.74		100.00

Table 4.5 (continued). Mixed model summary for chemesthetic and texture attributes.

Heat	Product	36.21	<.0001							
				Panelist	0.33	0.23	-0.12	0.78	0.1492	6.45
				Product*Panelist	-0.25	0.36	-0.95	0.45	0.4864	0.00
				Residual	4.78	0.51	3.92	5.96		93.55
Texture										
Slipperiness	Product	42.18	<.0001							
				Panelist	0.04	0.05	-0.05	0.14	0.3864	2.42
				Product*Panelist	0.42	0.14	0.15	0.70	0.0025	24.52
				Residual	1.26	0.13	1.03	1.57		73.05
				Total	1.72	0.14	1.47	2.04		100.00
Hardness	Product	17.69	<.0001							
				Panelist	0.14	0.10	-0.07	0.34	0.1857	6.38
				Product*Panelist	0.46	0.17	0.14	0.79	0.005	21.71
				Residual	1.54	0.16	1.26	1.92		71.91
				Total	2.14	0.19	1.81	2.57		100.00
Crispness	Product	43.62	<.0001							
				Panelist	0.33	0.22	-0.10	0.76	0.1293	10.83
				Product*Panelist	0.66	0.23	0.22	1.11	0.0036	21.52
				Residual	2.08	0.22	1.70	2.59		67.65
				Total	3.07	0.31	2.54	3.78		100.00
Fracturability	Product	15.49	<.0001							
				Panelist	0.26	0.18	-0.10	0.62	0.1525	6.91
				Product*Panelist	0.00	0.28	-0.55	0.55	0.9955	0.00
				Residual	3.54	0.38	2.91	4.42		93.09
				Total	3.81	0.42	3.10	4.79		100.00
Crunchiness	Product	11.96	<.0001							

Table 4.5 (continued). Mixed model summary for chemesthetic and texture attributes.

				Panelist	0.00	0.02	-0.04	0.04	0.8585	0.00
				Product*Panelist	0.36	0.12	0.14	0.59	0.0017	26.23
				Residual	1.02	0.11	0.83	1.27		73.77
				Total	1.38	0.12	1.18	1.64		100.00
Juiciness	Product	21.80	<.0001							
				Panelist	0.08	0.07	-0.06	0.22	0.2707	3.22
				Product*Panelist	0.03	0.19	-0.34	0.41	0.8618	1.33
				Residual	2.38	0.25	1.95	2.97		95.44
				Total	2.49	0.20	2.14	2.94		100.00
Skin awareness	Product	42.10	<.0001							
				Panelist	1.03	0.60	-0.15	2.21	0.0868	24.60
				Product*Panelist	1.03	0.27	0.50	1.56	0.0001	24.55
				Residual	2.13	0.23	1.75	2.66		50.85
				Total	4.19	0.66	3.15	5.85		100.00
Fibrousness	Product	13.04	<.0001							
				Panelist	0.52	0.29	-0.05	1.10	0.0752	39.07
				Product*Panelist	0.37	0.07	0.23	0.51	<.0001	27.75
				Residual	0.44	0.05	0.36	0.55		33.18
				Total	1.33	0.30	0.90	2.20		100.00

Table 4.6 Mean aroma intensities for the various products evaluated for lexicon validation. Same statistical lettering within columns indicates no significant difference ($p > 0.05$) among products for that attribute.

Product	Vinegar (a)	Burnt (a)	Smoky (a)	Bell pepper (a)	Floral (a)	Fruity (a)	Spicy (a)	Woody (a)	Green (a)	Earthy (a)	Cooked tomato (a)	Cooked vegetable (a)	Sweet aromatics (a)
1	0 d	0 c	0 b	6.16 a	2.19 bcde	2.06\ def	0.19 ef	1.56 abcd	5.19 a	1.5 ab	0 e	0 g	0.94 ef
2	0 d	0 c	0.03 b	5.53 a	4.04 a	3.26 abcde	0 f	1.09 abcd	2.97 bcd	1.13 abc	0.02 e	0 g	1.47 cdef
3	0.01 d	0.01 c	0.01 b	6.25 a	3.75 ab	3.37 abcd	0.01 f	1.25 abcd	2.99 bcd	1.13 abc	0.01 e	0.01 g	1.4 cdef
4	0 d	0 c	0 b	5.94 a	4.56 a	3.13 bcde	0 f	1.13 abcd	2.82 bcde	1.07 abc	0 e	0.01 g	1.25 def
5	0 d	0.13 c	0.45 b	4.79 a	3 abc	2.38 cde	2.84 de	1.75 abc	4.81 ab	1.22 abc	0.31 de	0.38 efg	1 ef
6	0 d	0.01 c	0.01 b	5.94 a	2.32 bcd	1.97 defg	1.65 def	2.04 ab	4.74 abc	1.06 abc	0 e	0.01 g	0.75 f
7	3.26 c	0.24 c	0.81 b	3.03 b	1 defg	2.44 cde	0.57 ef	1.13 abcd	0.34 h	1.06 abc	1.68 cd	2.44 bcd	2.33 abcd
8	3.77 c	0 c	0 b	3 b	3.07 abc	4.81 a	4.22 bcd	1.07 abcd	0.69 fgh	0.88 abc	1 cde	1.52 cdefg	3.25 a
9	4.57 c	0.07 c	0.01 b	2.06 b	0.25 fg	1.91 defg	2.53 def	2.03 ab	3.13 bcd	1.94 a	0.5 de	3.56 ab	0.88 ef
10	1.94 cd	0.13 c	0.13 b	2.56 b	1.85 cdef	3.73 abc	1.5 def	1.45 abcd	0.63 gh	1.01 abc	2.06 bc	1.79 bcdefg	2.78 ab
11	4.94 c	0 c	0.07 b	2.22 b	0.53 fg	2.31 cde	2.75 de	1.72 abc	2.5 defg	1.66 a	0.26 de	2.25 bcde	1.25 def
12	4.63 c	0 c	0.04 b	2.38 b	0.47 fg	2.44 cde	3.77 cd	1.31 abcd	2.66 def	1.16 abc	0 e	1.58 bcdefg	1.51 cdef
13	10.23 ab	0.01 c	0.01 b	2.48 b	0.38 fg	3.34 abcd	6.25 abc	0.59 bcd	1.36 defgh	0.13 c	0.13 e	0.78 defg	1.53 cdef
14	8.38 b	0 c	0 b	2.94 b	1.56 cdefg	4.19 ab	5.69 abc	0.38 cd	1.31 defgh	0.19 bc	0.01 e	0.49 defg	2.59 abc
15	11.13 ab	0 c	0.01 b	2.82 b	0.13 g	4.19 ab	6.62 ab	0.13 d	0.91 efgh	0 c	0.01 e	0.06 g	2 bcde
16	12.19 a	0 c	0 b	2.66 b	0.31 fg	3.89 abc	6.84 ab	0.07 d	0.84 efgh	0.07 c	0 e	0.19 fg	1.56 bcdef

Table 4.6 (continued). Mean aroma intensities for the various products evaluated for lexicon validation. Same statistical lettering within columns indicates no significant difference ($p > 0.05$) among products for that attribute.

17	3.6 c	0.01 c	0.06 b	2.19 b	0.5 fg	1.69 efgh	3.84 cd	1.57 abcd	2.75 cde	1.53 ab	0.44 de	3.38 abc	1 ef
18	9.03 b	0 c	0.07 b	1.96 b	0.64 efg	2.44 cde	7 a	1.04 abcd	1.73 defgh	0.88 abc	0 e	2.13 bcdef	1.67 bcdef
19	0.11 d	2.09 b	5.5 a	1.82 b	0.19 g	0.41 gh	0.19 ef	2.06 ab	0.06 h	1.51 ab	4.19 a	4.52 a	1.57 bcdef
20	0 d	2.81 ab	5.48 a	1.69 b	0.66 efg	0.51 fgh	0.13 ef	2.28 a	0.19 h	1.69 a	3.37 ab	4.56 a	1.09 ef
21	0 d	2.13 b	5.47 a	1.93 b	0 g	0.25 h	0 f	1.84 abc	0 h	1.59 a	3.54 ab	4.82 a	0.94 ef
22	0.01 d	3.25 a	5.23 a	1.66 b	0.19 g	0.25 h	0 f	2.48 a	0.01 h	1.54 ab	3.66 a	4.72 a	1.04 ef

Table 4.7 Mean flavor intensities for the various products evaluated for lexicon validation. Same statistical lettering within colums indicates no significant difference ($p > 0.05$) among products for that attribute.

Product	Vinegar (f)	Burnt (f)	Smoky (f)	Bell pepper (f)	Floral (f)	Fruity (f)	Spicy (f)	Woody (f)	Green (f)	Earthy (f)	Cooked tomato (f)	Cooked vegetable (f)	Sweet aromatics (f)	Metallic (f)	Sweet	Salty	Sour	Bitter	Umami
1	0 f	0.01 c	0 b	7.26 a	2.53 bc	2.07 cdefgh	0.06 f	2.31 abcd	5.56 a	1.41 abc	0 d	0.01 g	1.18 c	0.06 c	2.21 ef	0 i	0 i	0.49 ef	0.06 d
2	0 f	0 c	0 b	7.21 a	3.91 ab	3.65 ab	0 f	1.12 cde	2.73 bcd	1.03 abc	0 d	0 g	2.12 bc	0 c	4 bcd	0.01 i	0.06 i	0.13 f	0.01 d
3	0.01 f	0.01 c	0.01 b	6.94 a	4.31 a	3.26 abcd	0 f	1.16 bcde	2.5 bcde	0.94 abc	0.01 d	0.01 g	2.08 bc	0.13 c	4.07 bcd	0 i	0 i	0.14 f	0.13 cd
4	0.01 f	0.01 c	0.01 b	7.69 a	4.26 a	3.13 abcde	0 f	1.38 bcde	3.13 bc	0.99 abc	0.01 d	0 g	1.94 bc	0.13 c	4.22 abcd	0 i	0.03 i	0.19 f	0.01 d
5	0.06 f	0.19 c	0.46 b	3.94 b	1.72 cde	1.87 defgh	7.13 abc	2 abcd	4.51 ab	0.81 abc	0.32 d	0.32 efg	0.98 c	0.14 c	1.75 f	0.32 hi	0.09 i	0.81 cdef	0.13 cd
6	0.01 f	0.01 c	0.01 b	6.75 a	2.49 bc	2.09 cdefgh	4.97 cde	2.26 abcd	5.63 a	1.44 ab	0.01 d	0 g	0.97 c	0.07 c	1.94 f	0 i	0 i	0.72 def	0.13 cd
7	4.97 de	0.06 c	0.41 b	3.35 bc	1.51 cde	3.31 abc	0.69 f	1.26 bcde	0.44 efgh	0.54 bc	2.03 bc	2.51 bcd	3.07 ab	0.63 abc	4.56 ab	1.96 efghi	3.93 efg	1.16 abcdef	0.66 cd
8	3.86 de	0.02 c	0.07 b	3.31 bc	2.57 bc	4.31 a	5.12 cde	1.12 bcde	0.63 defgh	0.47 bc	1.12 cd	1.44 defg	3.94 a	0.39 bc	5.81 a	1.29 fghi	3.28 fgh	1.07 abcdef	0.38 cd
9	5.78 d	0.06 c	0 b	2.29 bc	0.38 e	1.59 fgh	2.43 ef	2.03 abcd	3.16 bc	2.01 a	0.32 d	2.82 abcd	0.98 c	0.94 abc	1.59 f	4.72 abcd	5.41 def	2.09 ab	0.88 bc
10	2.19 ef	0.06 c	0.01 b	2.32 bc	2.03 cd	3.09 abcde	0.72 f	1.44 bcde	0.63 defgh	0.91 abc	2.84 ab	2.13 cde	3.04 ab	0.81 abc	4.26 abc	0.94 ghi	1.94 ghi	1.78 abcd	0.63 cd
11	6.34 cd	0 c	0.13 b	2.88 bc	0.41 de	2.37 bcdefgh	3.53 de	1.1 cde	2.4 bcdef	1.25 abc	0.37 d	1.84 cdefg	2.14 bc	0.19 c	3.72 bcde	2.82 cdefg	5.6 def	0.88 bcdef	0.32 cd

Table 4.7 (continued). Mean flavor intensities for the various products evaluated for lexicon validation. Same statistical lettering within colums indicates no significant difference ($p > 0.05$) among products for that attribute.

12	5.69 d	0 c	0.03 b	2.84 bc	0.43 de	2.57 bcdefg	4.37 de	1.39 bcde	2.25 cdefg	0.81 abc	0 d	2.04 cdef	2.1 bc	0.38 bc	3.95 bcd	2.69 defgh	5.35 def	0.57 def	0.62 cd
13	10.19 ab	0.01 c	0 b	2.6 bc	0.19 e	2.19 cdefgh	5.99 bcd	0.76 de	1.5 cdefgh	0.22 bc	0.01 d	1.19 defg	1.53 c	0.21 c	1.91 f	3.75 bcdef	9.19 abc	0.56 def	0.26 cd
14	10.44 ab	0 c	0 b	2.81 bc	1.69 cde	2.88 bcdef	4.58 cde	0.75 de	1.6 cdefgh	0.19 bc	0.01 d	0.55 efg	2.15 bc	0.31 c	2.66 cdef	3.81 bcde	8.22 bcd	0.94 bcdef	0.22 cd
15	12.32 ab	0 c	0.01 b	2.73 bc	0.14 e	2.06 cdefgh	4.91 cde	0.1625 e	1.03 cdefgh	0.01 c	0.01 d	0.19 fg	1.88 bc	1.25 abc	2.69 cdef	4.25 bcde	10.68 ab	0.38 f	0.13 cd
16	13.44 a	0.01 c	0.01 b	2.38 bc	0.19 e	1.81 efgh	4.19 de	0 e	1.06 cdefgh	0.01 c	0.01 d	0.19 fg	1.81 bc	0.13 c	2.56 def	2.88 cdefg	11.38 a	0.26 f	0.14 cd
17	4.91 de	0.01 c	0.25 b	2.19 bc	0.56 de	1.06 h	8.71 a	1.73 abcd	2.91 bc	1.22 abc	0.45 cd	3.38 abc	1.19 c	0.94 abc	1.25 f	4.19 bcde	6.41 cde	1 bcdef	0.63 cd
18	9.44 bc	0.01 c	0.04 b	3.23 bc	0.32 e	1.57 fgh	8.13 ab	0.81 de	2.03 cdefgh	0.76 abc	0 d	1.88 cdefg	1.57 c	0.32 c	1.69 f	3.41 bcdefg	7.76 bcd	0.68 def	0.47 cd
19	0.01 f	2.84 b	5.06 a	1.85 bc	0.63 de	1.79 efgh	0 f	2.66 abc	0.07 h	0.94 abc	4.03 a	4.22 ab	1.82 bc	1.25 abc	2.71 cdef	3.73 bcdef	0.5 hi	1.66 abcde	1.51 ab
20	0.06 f	3.38 b	5.4 a	1.78 bc	0.48 de	1.64 fgh	0.44 f	3.19 a	0.25 fgh	0.93 abc	3.75 a	4.33 ab	1.23 c	1.74 ab	1.97 f	5.88 ab	0.6 hi	2.03 abc	1.73 a
21	0 f	2.97 b	5.53 a	1.88 bc	0.19 e	1.25 gh	0 f	2.69 ab	0.09 gh	0.57 bc	3.79 a	4.38 ab	1.19 c	1.21a bc	1.94 f	7.03 a	0.06 i	1.32 abcdef	1.73 a
22	0.13 f	4.34 a	4.69 a	1.63 c	0.19 e	1.01 h	0.01 f	3.09 a	0.07 h	0.94 abc	4.19 a	4.66 a	1.29 c	1.91 a	1.75 f	5.25 abc	0.76 hi	2.29 a	1.69 a

Table 4.8 Mean texture intensities for the various products evaluated for lexicon validation. Same statistical lettering within columns indicates no significant difference ($p > 0.05$) among products for that attribute.

Product	Slipperiness	Hardness	Crispness	Fracturability	Crunchiness	Juiciness	Skin awareness	Fibrousness
1	0.81 e	8.88 ab	10.68 a	7.69 ab	5.38 abc	9.01 abc	8.69 abc	0.31 d
2	1 de	8.1 abc	10.75 a	7.94 a	5.03 abc	9.81 a	8.14 abc	0.06 d
3	1.04 de	7.85 abcd	10.19 ab	7.88 a	4.66 abcd	9.73 ab	8.16 abc	0.26 d
4	1.13 de	8.19 abc	10.48 a	7.6 ab	4.88 abc	10.16 a	8.69 abc	0.25 d
5	1.25 de	8.59 abc	10.31 ab	7.5 ab	5.45 abc	7.72 bcd	8.35 abc	0.38 d
6	1.19 de	9.31 a	10.03 ab	8 a	5.82 a	7.38 cde	8.26 abc	0.38 d
7	4.44 b	5.87 ef	4.31 hij	4.66 cdef	3.97 cde	7.06 cdefg	6.28 c	1.5 bcd
8	1.33 de	5.69 ef	5.03 fghi	3.62 def	4.13 bcde	5.06 ghijk	8.31 abc	0.79 d
9	1.44 de	7.25 bcde	4.49 ghij	3.48 ef	4.56 abcd	4.89 ijk	8.86 ab	0.56 d
10	4.13 bc	5.13 f	5.16 fghi	4.44 cdef	4.01 bcde	4.59 jk	8.38 abc	1.25 cd
11	2.28 de	8.37 abc	6.91 def	4.78 cdef	5.47 ab	5.45 efghijk	8.25 abc	0.57 d
12	1.53 de	8.13 abc	6.75 def	4.21 cdef	5.24 abc	5.44 efghijk	8.69 abc	0.44 d
13	0.84 e	8.88 ab	5.67 efgh	2.31 f	5.06 abc	3.86 k	9.97 a	0.75 d
14	1.03 de	8.44 abc	8.1 bcd	3.56 def	5.44 abc	4.72 jk	9.13 a	0.22 d
15	1.16 de	8.12 abc	7.81 cde	3.71 def	5.09 abc	5.25 fghijk	9.06 a	0.19 d
16	1 de	7.51 abcde	6.59 defg	3.22 ef	4.78 abcd	4.98 hijk	8.89 ab	0.14 d
17	2.59 cd	6.84 cdef	5.26 fgh	6.05 abcd	4.66 abcd	6.82 defghi	6.44 bc	0.31 d
18	1.66 de	9.28 a	9.66 abc	6.63 abc	6 a	6.19 defghij	8 abc	0.39 d
19	6.75 a	2.9 g	0.78 k	3.38 ef	1.31 f	6.25 defghij	0.19 d	3.13 a
20	7.56 a	5.13 f	2.47 jk	5.31 bcde	2.74 ef	7.69 cd	0.5 d	2.83 ab
21	7.18 a	6.22 def	2.94 ijk	3.96 def	3.38 de	6.92 defgh	0 d	2.66 abc
22	6.91 a	5.78 ef	3.01 ij	5.01 cde	2.79 ef	7.09 cdef	0.08 d	2.62 abc

Table 4.9 Mean chemical feeling factor intensities for the various products evaluated for lexicon validation. Same statistical lettering within columns indicates no significant difference ($p > 0.05$) among products for that attribute.

Product	Astringency	Pungency (a)	Pungency	TTB	Heat
1	0.19 ij	0.13 f	0.04 f	0.01 f	0 e
2	0.13 j	0.06 f	0 f	0 f	0 e
3	0.19 ij	0.13 f	0.07 f	0 f	0.06 de
4	0.01 j	0 f	0.06 f	0 f	0.01 e
5	0.81 ghij	1.39 ef	3.75 abcd	8.9 a	8.63 a
6	0.56 hij	0.38 f	2.75 cde	5.31 bc	5.16 b
7	1.94 cdefg	1.14 ef	0.98 ef	0.81 ef	0.08 de
8	1.94 cdefg	2.98 de	3.01 bcde	4.53 cd	4.71 b
9	1.47 efghi	2.89 de	2.19 def	1.84 def	1.13 cde
10	0.57 hij	1.19 ef	0.48 f	0.41 ef	0.32 de
11	2 bcdefg	2.81 de	3.12 bcde	4.07 cd	3.94 bc
12	1.81 defgh	3.81 cd	2.9 bcde	4.03 cd	3.72 bc
13	3.19 abc	6.51 ab	4.81 abc	5.44 bc	5.38 b
14	3.09 abcd	5.31 bc	3.63 bcd	3 cde	2.84 bcd
15	4.22 a	7.13 ab	4.34 abcd	3.85 cd	3.66 bc
16	3.28 ab	7.56 a	5.06 ab	3.97 cd	3.31 bc
17	2.58 bcde	2.81 de	4.97 ab	9.31 a	9.56 a
18	2.43 bcdef	6.72 ab	5.93 a	7.85 ab	8.22 a
19	1.32 efghij	0.26 f	0.19 f	0.13 ef	0.01 e
20	1.56 efgh	0.31 f	0.07 f	0.44 ef	0.38 de
21	1 ghij	0.13 f	0 f	0.01 f	0 e
22	1.16 fghij	0.25 f	0 f	0.13 ef	0.19 de

FIGURES

Sensory Lexicon for Fresh and Preserved Peppers

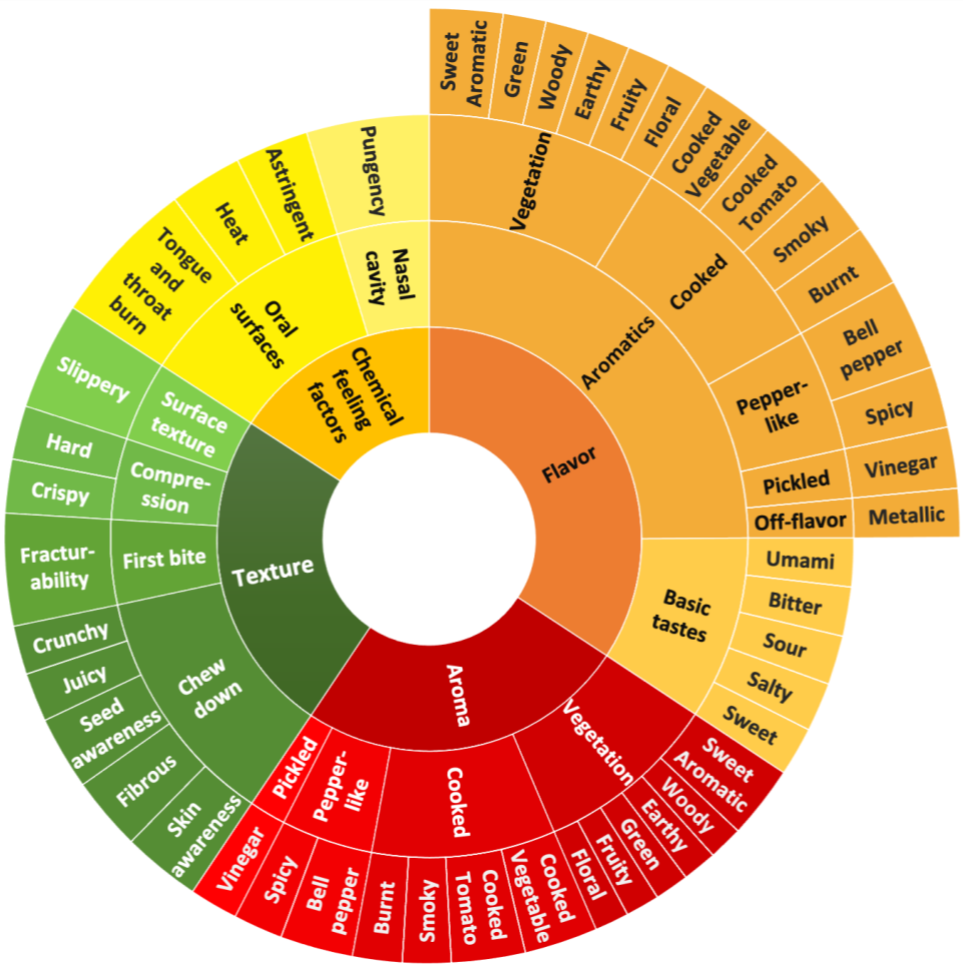

Figure 4.1. Flavor and texture wheel for fresh and preserved peppers

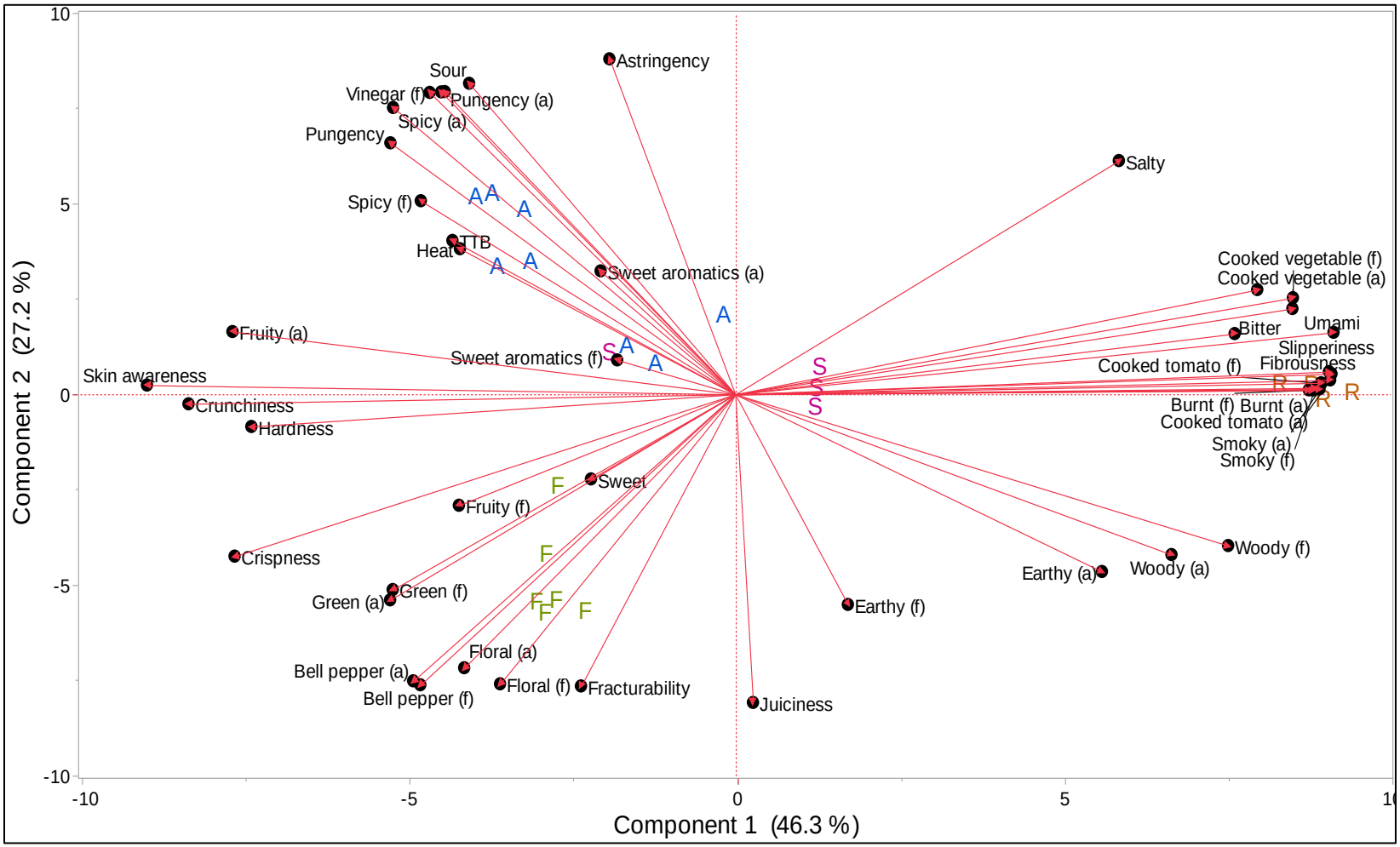

Figure 4.2. Principal component biplot showing attribute loadings for the entire set of products evaluated for lexicon validation. F – Fresh peppers, S – Sweet acidified pepper products, A – Acidified pepper products, R – Roasted pepper products, (a) - aroma, (f) - flavor

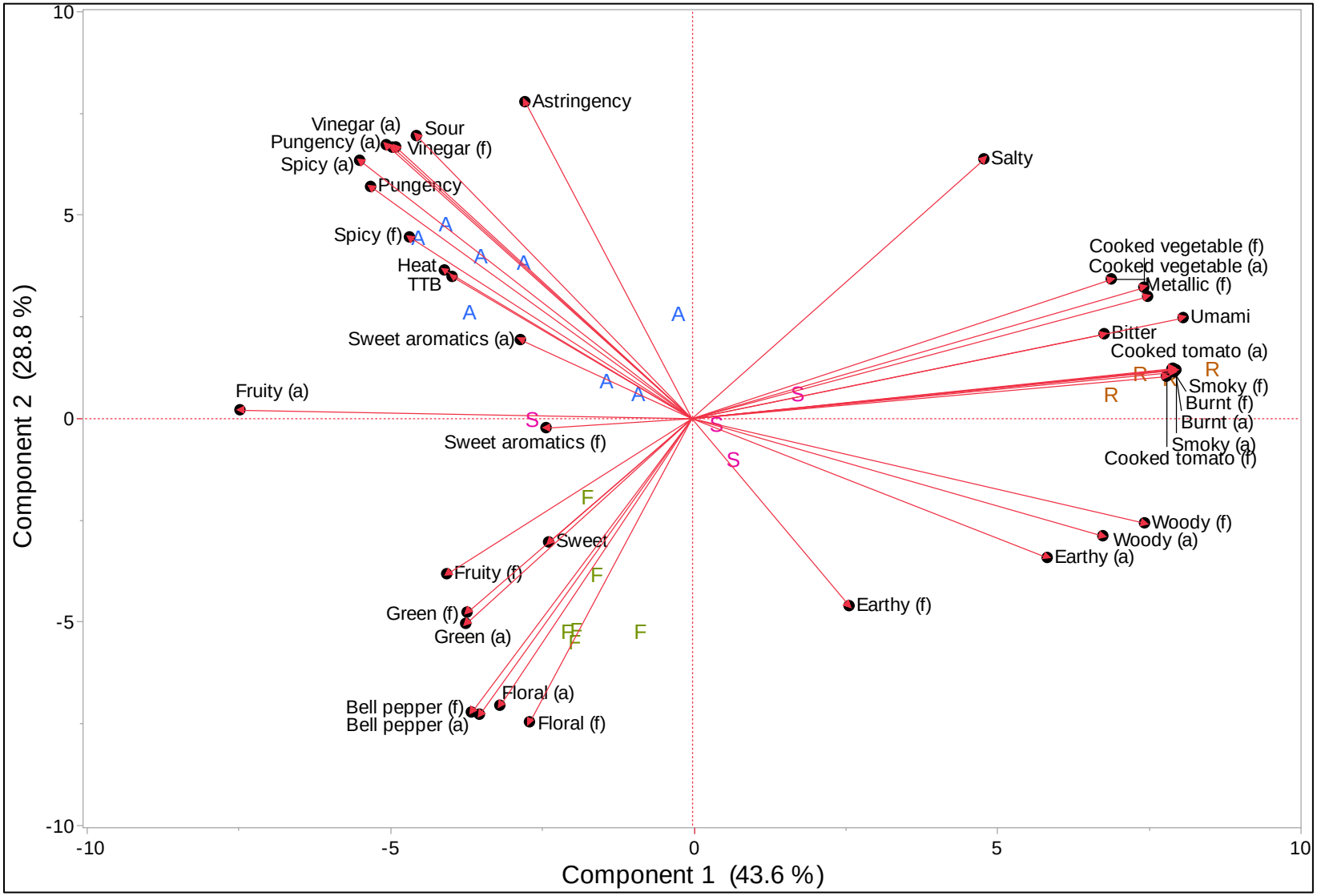

Figure 4.3. Principal component biplot depicting product differentiation by flavor. F – Fresh peppers, S – Sweet acidified pepper products, A – Acidified pepper products, R – Roasted pepper products, (a) - aroma, (f) - flavor

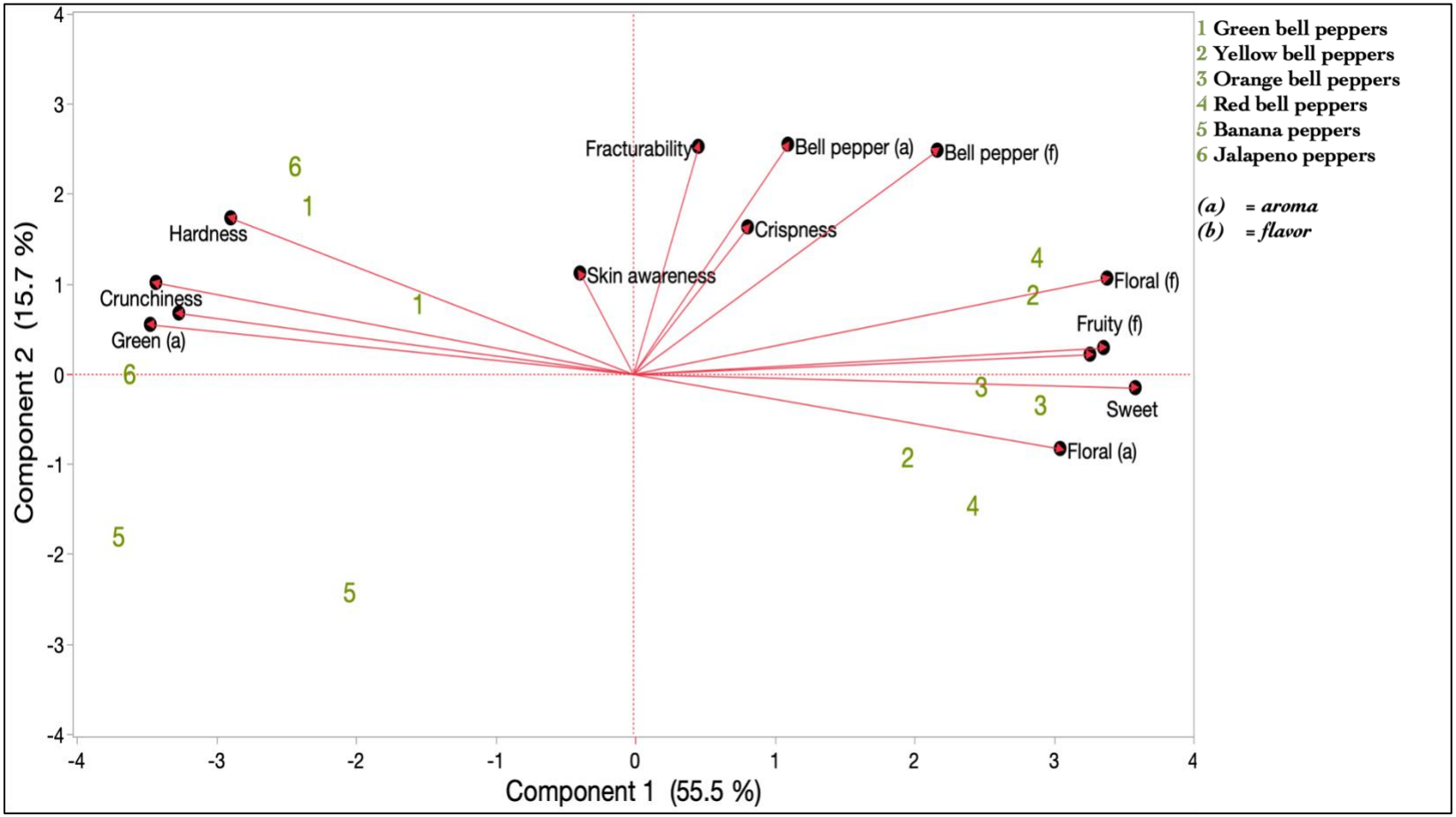

Figure 4.4. Principal component biplot depicting differentiation among fresh peppers.

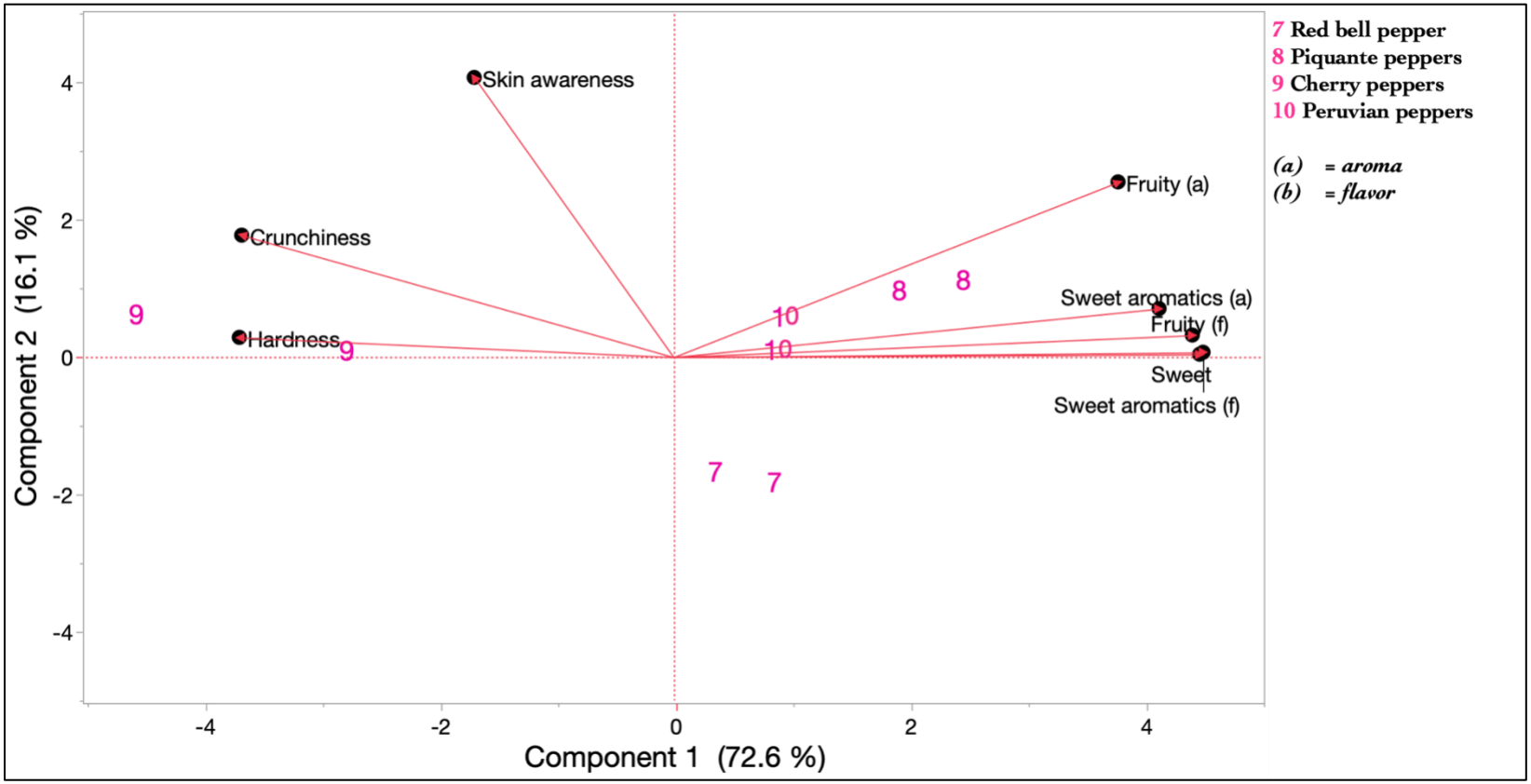

Figure 4.5. Principal components biplot depicting differentiation among sweet-brined pepper products.

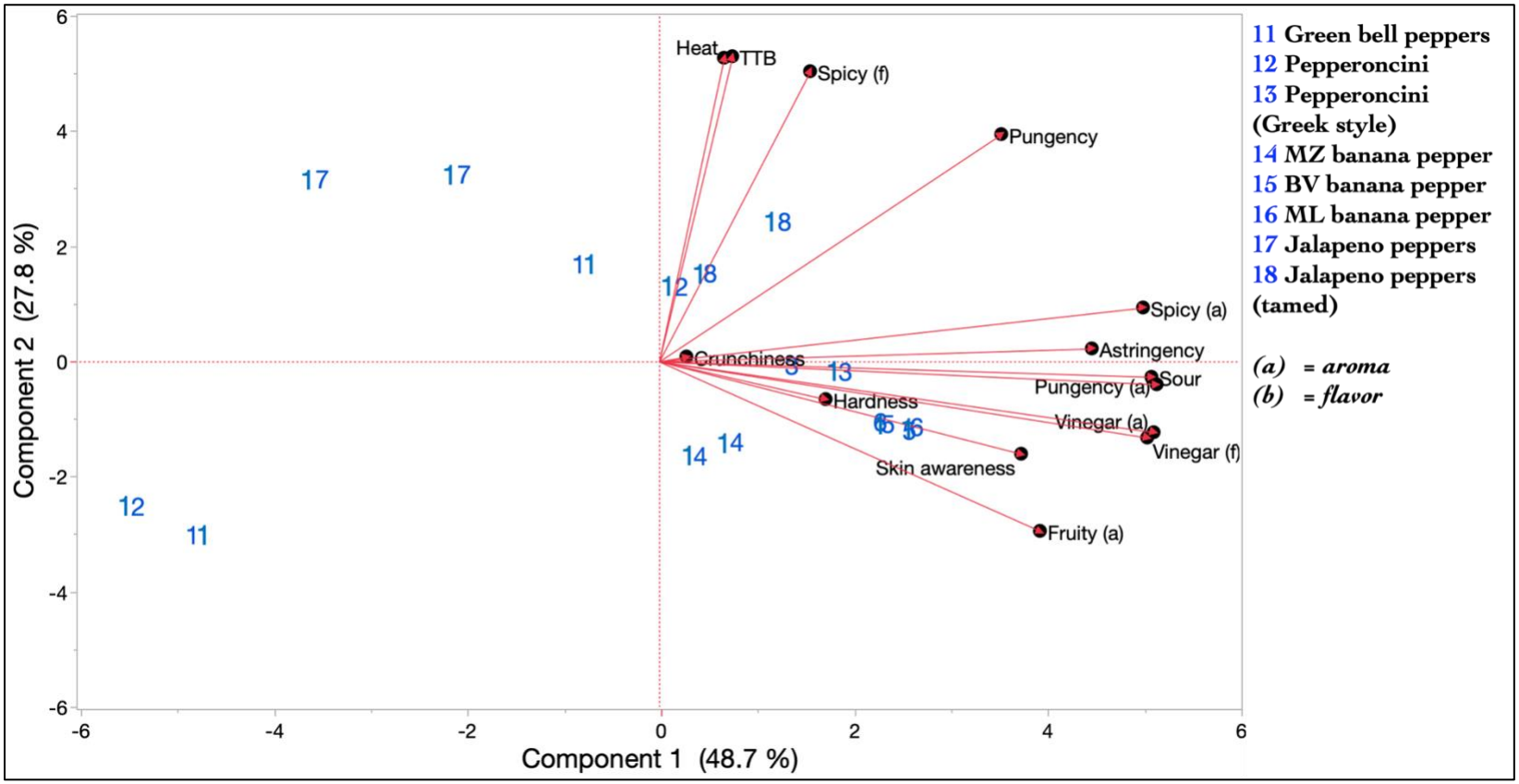

Figure 4.6. Principal component biplot depicting differentiation among acidified pepper products.

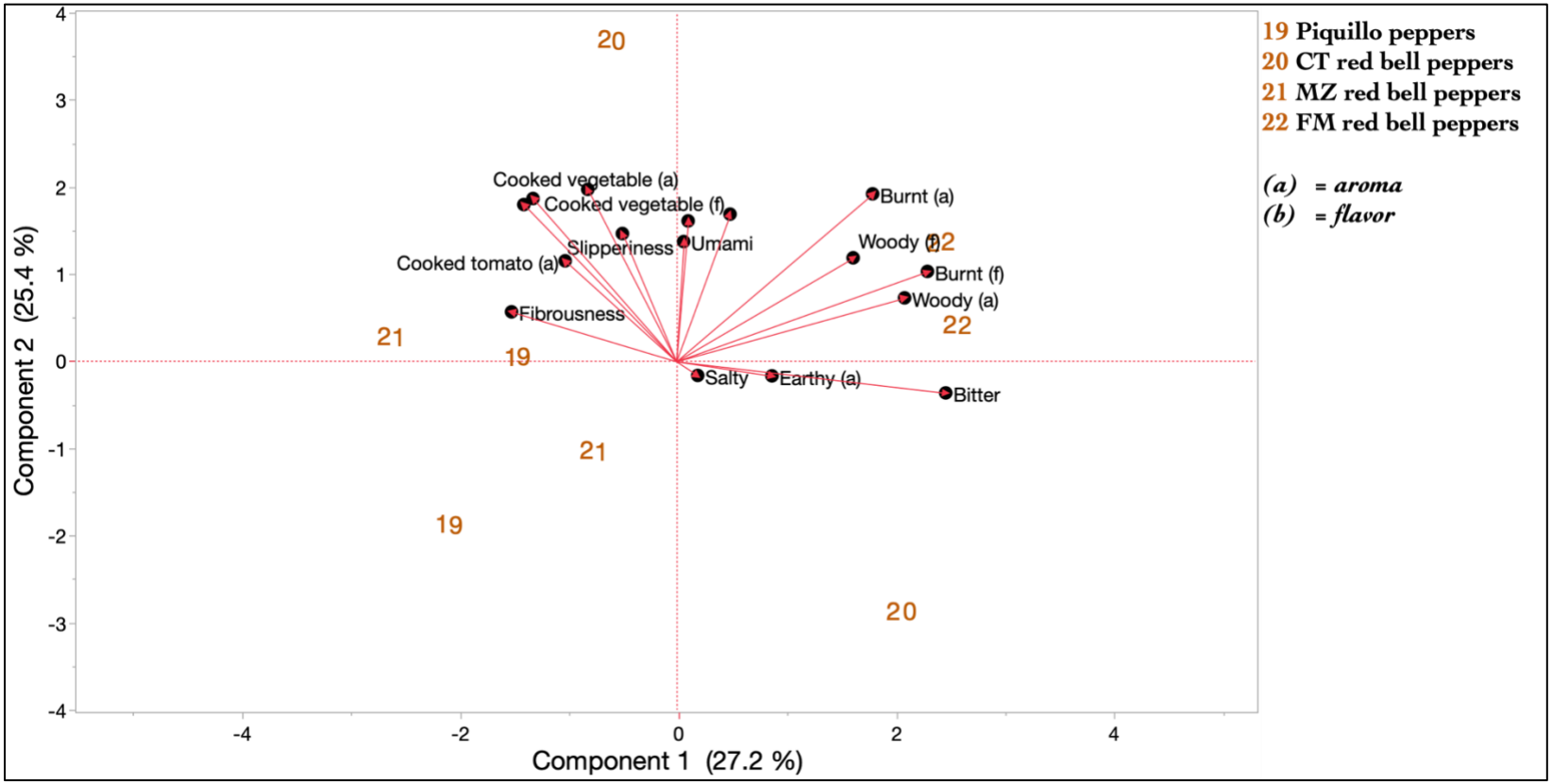

Figure 4.7 Principal component biplot depicting differentiation among roasted pepper products.

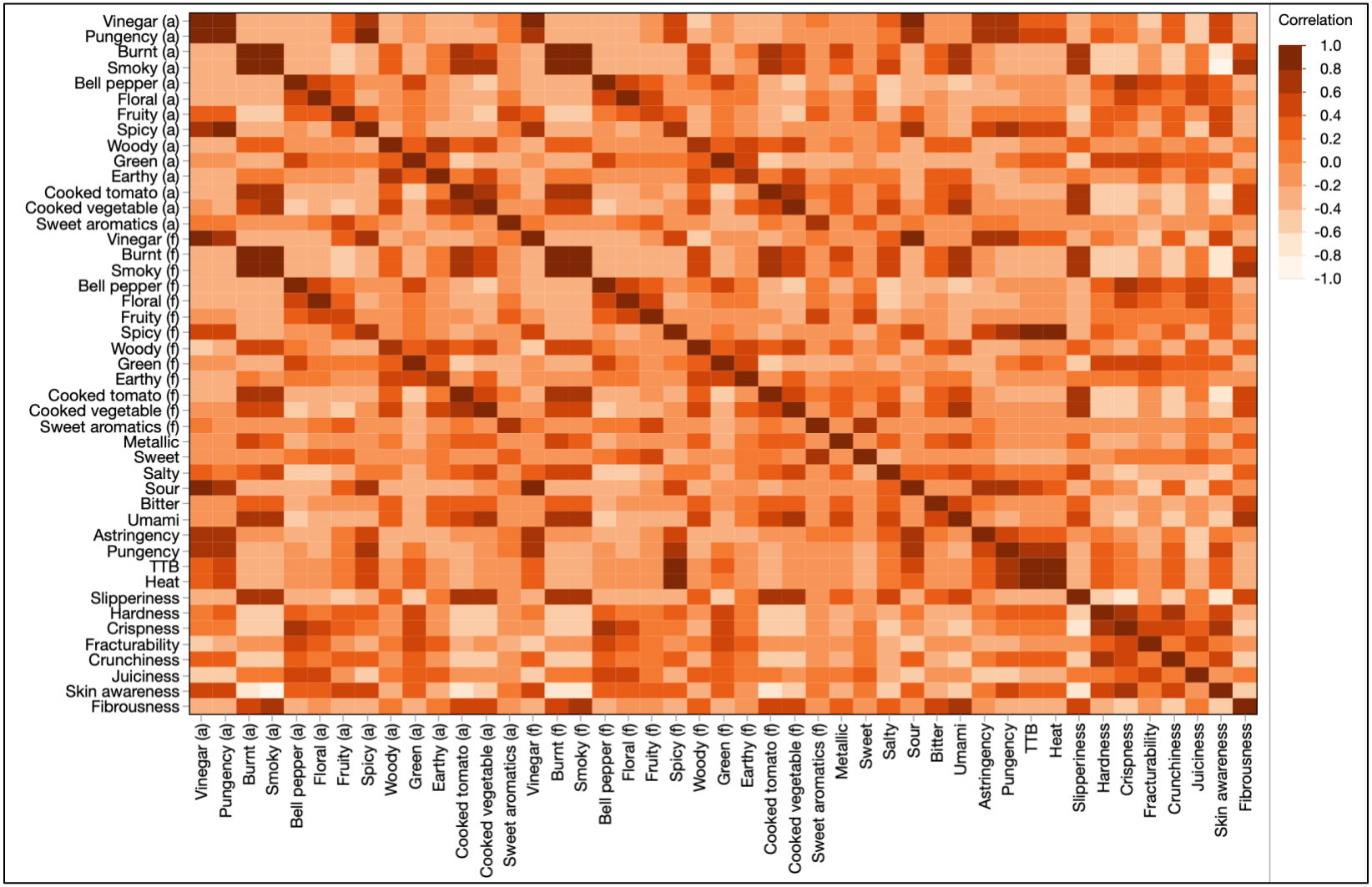

Figure 4.8. Correlation analysis to identify collinear attributes and eliminate redundancies.

REFERENCES

Biswas, T., Guan, Z., & Wu, F. (2018). An Overview of the US Bell Pepper Industry. *IFAS Extension*. Retrieved February 20, 2022, from https://edis.ifas.ufl.edu/publication/FE1028

Buttery, R. G., Seifert, R. M., Guadagni, D. G., & Ling, L. C. (1969). Characterization of some volatile constituents of bell peppers. *Journal of Agricultural and Food Chemistry*, *17*(6), 1322–1327.

Carvalho, A. V., de Andrade Mattietto, R., de Oliveira Rios, A., de Almeida Maciel, R., Moresco, K. S., & de Souza Oliveira, T. C. (2015). Bioactive compounds and antioxidant activity of pepper (Capsicum sp.) genotypes. *Journal of Food Science and Technology*, *52*(11), 7457–7464.

Castillejo, N., Martínez-Zamora, L., & Artés-Hernández, F. (2022). Postharvest UV radiation enhanced biosynthesis of flavonoids and carotenes in bell peppers. *Postharvest Biology and Technology*, *184*, 111774.

Chambers, E., Sanchez, K., Phan, U. X. T., Miller, R., Civille, G. V., & Donfrancesco, B. D. (2016). Development of a "living" lexicon for descriptive sensory analysis of brewed coffee. *Journal of Sensory Studies*, *31*(6), 465–480.

Chen, J., Hu, Y., Wang, J., Hu, H., & Cui, H. (2016). Combined Effect of Ozone Treatment and Modified Atmosphere Packaging on Antioxidant Defense System of Fresh-Cut Green Peppers. *Journal of Food Processing and Preservation*, *40*(5), 1145–1150.

Chun, S., Chambers, E., & Han, I. (2020). Development of a Sensory Flavor Lexicon for Mushrooms and Subsequent Characterization of Fresh and Dried Mushrooms. *Foods*, *9*(8), 980. Multidisciplinary Digital Publishing Institute.

Conforti, F. d., & Zinck, J. b. (2002). Hydrocolloid-Lipid Coating Affect on Weight Loss, Pectin Content, and Textural Quality of Green Bell Peppers. *Journal of Food Science*, *67*(4), 1360–1363.

Da Conceicao Neta, E. R., Johanningsmeier, S. D., Drake, M. A., & McFeeters, R. F. (2007). A chemical basis for sour taste perception of acid solutions and fresh-pack dill pickles. *Journal of Food Science*, *72*(6), S352-359.

Eggink, P. M. (2013). *A taste of pepper: Genetics, biochemistry and prediction of sweet pepper flavor* (PhD Thesis). Wageningen University, Netherlands. Retrieved September 3, 2021, from https://research.wur.nl/en/publications/a-taste-of-pepper-genetics-biochemistry-and-prediction-of-sweet-p

Eggink, P. M., Maliepaard, C., Tikunov, Y., Haanstra, J. P. W., Bovy, A. G., & Visser, R. G. F. (2012). A taste of sweet pepper: Volatile and non-volatile chemical composition of fresh sweet pepper (Capsicum annuum) in relation to sensory evaluation of taste. *Food Chemistry*, *132*(1), 301–310.

Fleming, H. P., Thompson, R. L., & McFeeters, R. F. (1993). Firmness Retention in Pickled Peppers as Affected by Calcium Chloride, Acetic Acid, and Pasteurization. *Journal of Food Science*, *58*(2), 325–330.

Godoy, R. C. B. de, Chambers, E., & Yang, G. (2020). Development of a preliminary sensory lexicon for mate tea. *Journal of Sensory Studies*, *35*(3), e12570.

González-Saucedo, A., Barrera-Necha, L. L., Ventura-Aguilar, R. I., Correa-Pacheco, Z. N., Bautista-Baños, S., & Hernández-López, M. (2019). Extension of the postharvest quality of bell pepper by applying nanostructured coatings of chitosan with Byrsonima crassifolia extract (L.) Kunth. *Postharvest Biology and Technology*, *149*, 74–82.

Guzmán, I., & Bosland, P. W. (2017). Sensory properties of chile pepper heat – and its importance to food quality and cultural preference. *Appetite*, *117*, 186–190.

Hongsoongnern, P., & Chambers, E. (2008). A Lexicon for Texture and Flavor Characteristics of Fresh and Processed Tomatoes. *Journal of Sensory Studies*, *23*(5), 583–599.

Hoppu, U., Puputti, S., & Sandell, M. (2021). Factors related to sensory properties and consumer acceptance of vegetables. *Critical Reviews in Food Science and Nutrition*, *61*(10), 1751–1761. Taylor & Francis.

Howard, L. R., Burma, P., & Wagner, A. B. (1994). Firmness and Cell Wall Characteristics of Pasteurized Jalapeño Pepper Rings Affected by Calcium Chloride and Acetic Acid. *Journal of Food Science*, *59*(6), 1184–1186.

Huffman, V. L., Schadle, E. R., Villalon, B., & Burns, E. E. (1978). VOLATILE COMPONENTS AND PUNGENCY IN FRESH AND PROCESSED JALAPENO PEPPERS. *Journal of Food Science*, *43*(6), 1809–1811. John Wiley & Sons, Ltd.

Jaffe, T. R., Wang, H., & Chambers, E. (2017). Determination of a lexicon for the sensory flavor attributes of smoked food products. *Journal of Sensory Studies*, *32*(3), e12262.

Jen, J. J., & Robinson, M. L. (1984). Pectolytic Enzymes in Sweet Bell Peppers (Capsicum annuum L.). *Journal of Food Science*, *49*(4), 1085–1087.

Jimenez-Garcia, S. N., Vazquez-Cruz, M. A., Miranda-Lopez, R., Garcia-Mier, L., Guevara-Gonzalez, R. G., & Feregrino-Perez, A. A. (2018). Effect of elicitors as stimulating substances on sensory quality traits in color sweet bell pepper (Capsicum annuum L. cv. Fascinato and Orangela) grown under greenhouse conditions. *Polish Journal of Food and Nutrition Sciences*, *68*(4). -. Retrieved September 22, 2021, from http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.agro-9cf61770-c5cf-43d3-8d02-7d700baedeeb

Johanningsmeier, S., Thompson, R. L., & Fleming, H. (2003). Bag-in-box technology: Sensory quality of pickles produced from process-ready, fermented cucumbers. *Pickle Pak Sci*, *8*.

Jun, H.-R., Cho, I.-H., Choi, H.-K., & Kim, Y.-S. (2005). Comparison of Volatile Components in Fresh and Dried Red Peppers (Capsicum annuum L.). *Food Science and Biotechnology*, *14*(3), 392–398. Korean Society of Food Science and Technology.

Koppel, K., & Chambers, E. (2010). Development and application of a lexicon to describe the flavor of pomegranate juice. *Journal of Sensory Studies*, *25*(6), 819–837.

Koskiniemi, C. B., Truong, V.-D., McFeeters, R. F., & Simunovic, J. (2013). Quality evaluation of packaged acidified vegetables subjected to continuous microwave pasteurization. *LWT - Food Science and Technology*, *54*(1), 157–164.

Lawless, L. J. R., & Civille, G. V. (2013). Developing Lexicons: A Review. *Journal of Sensory Studies*, *28*(4), 270–281.

Lawless, L. J. r, Hottenstein, A., & Ellingsworth, J. (2012). The mccormick spice wheel: A systematic and visual approach to sensory lexicon development. *Journal of Sensory Studies*, *27*(1), 37–47.

Ledeker, C. N., Suwonsichon, S., Chambers, D. H., & Adhikari, K. (2014). Comparison of sensory attributes in fresh mangoes and heat-treated mango purées prepared from Thai cultivars. *LWT - Food Science and Technology*, *56*(1), 138–144.

Lee, Y., & Howard, L. (1999). Firmness and Phytochemical Losses in Pasteurized Yellow Banana Peppers (Capsicum annuum) As Affected by Calcium Chloride and Storage. *Journal of Agricultural and Food Chemistry*, *47*(2), 700–703. American Chemical Society.

Loizzo, M. R., Pugliese, A., Bonesi, M., Menichini, F., & Tundis, R. (2015). Evaluation of chemical profile and antioxidant activity of twenty cultivars from Capsicum annuum, Capsicum baccatum, Capsicum chacoense and Capsicum chinense: A comparison between fresh and processed peppers. *LWT - Food Science and Technology*, *64*(2), 623–631.

Lotong, V., Iv, E. C., & Chambers, D. H. (2000). Determination of the Sensory Attributes of Wheat Sourdough Bread. *Journal of Sensory Studies*, *15*(3), 309–326.

Lownds, N. K., Banaras, M., & Bosland, P. W. (1994). Postharvest Water Loss and Storage Quality of Nine Pepper (Capsicum) Cultivars. *HortScience*, *29*(3), 191–193. American Society for Horticultural Science.

Luning, P. A., de Rijk, T., Wichers, H. J., & Roozen, J. P. (1994). Gas Chromatography, Mass Spectrometry, and Sniffing Port Analyses of Volatile Compounds of Fresh Bell Peppers (Capsicum annuum) at Different Ripening Stages. *Journal of Agricultural and Food Chemistry*, *42*(4), 977–983.

Luning, P. A., van der Vuurst de Vries, R., Yuksel, D., Ebbenhorst-Seller, T., Wichers, H. J., & Roozen, J. P. (1994). Combined Instrumental and Sensory Evaluation of Flavor of Fresh Bell Peppers (Capsicum annuum) Harvested at Three Maturation Stages. *Journal of Agricultural and Food Chemistry*, *42*(12), 2855–2861. American Chemical Society.

Luning, P. A., Yuksel, D., Vries, R. V. D. V. D., & Roozen, J. P. (1995). Aroma Changes in Fresh Bell Peppers (Capsicum annuum) after Hot-air Drying. *Journal of Food Science*, *60*(6), 1269–1276.

Martin, C., Maire, A., Chabanet, C., & Issanchou, S. (2015). Equi-intensity across the Spectrum™ taste scales. *Food Quality and Preference*, *44*, 75–83.

Martinez, M., Santos, C. P. dos, Verruma-Bernardi, M. R., Carrilho, E. N. V. M., Silva, P. P. M. da, Spoto, M. H. F., Ciarrocchi, I. R., et al. (2021). Agronomic, physical–chemical and sensory evaluation of pepper hybrids (Capsicum chinense Jacquin). *Scientia Horticulturae*, *277*, 109819.

McCall, C. (2021, September 15). Texas A&M AgriLife turns up heat on U.S. hot pepper market. *AgriLife Today*. Retrieved February 20, 2022, from https://agrilifetoday.tamu.edu/2021/09/15/agrilife-researchers-turn-up-heat-on-us-hot-pepper-market/

McFeeters, R. F., Barrangou, L. M., Barish, A. O., & Morrison, S. S. (2004). Rapid Softening of Acidified Peppers: Effect of Oxygen and Sulfite. *Journal of Agricultural and Food Chemistry*, *52*(14), 4554–4557. American Chemical Society.

Meilgaard, M. C., Civille, G. V., & Carr, B. T. (2016). *Sensory Evaluation Techniques*. Food science & technology (5th ed.). Boca Raton, FL: Taylor & Francis.

Naves, E. R., de Ávila Silva, L., Sulpice, R., Araújo, W. L., Nunes-Nesi, A., Peres, L. E. P., & Zsögön, A. (2019). Capsaicinoids: Pungency beyond Capsicum. *Trends in Plant Science*, *24*(2), 109–120.

Papageorge, L. M., McFeeters, R. F., & Fleming, H. P. (2003). Factors Influencing Texture Retention of Salt-free, Acidified, Red Bell Peppers during Storage. *Journal of Agricultural and Food Chemistry*, *51*(5), 1460–1463.

Patel, K., Calderon, R., Asencios, E., Vilchez, D., Marcelo, M., & Rojas, R. (2016). Agro-morphological Characteristics and Sensory Evaluation of Native Peruvian Chili Peppers. *Journal of Agricultural Science and Technology B*, *6*(3). Retrieved February 20, 2022, from http://www.davidpublisher.org/index.php/Home/Article/index?id=30886.html

Rosales, C. K., & Suwonsichon, S. (2015). Sensory Lexicon of Pomelo Fruit over Various Cultivars and Fresh-Cut Storage. *Journal of Sensory Studies*, *30*(1), 21–32.

Rosenberg, L. B. (2013). *Texture Retention in Pickles Produced from Commercial Scale Cucumber Fermentation using Calcium Chloride instead of Sodium Chloride*. Produced: [Raleigh, North Carolina] : North Carolina State University, 2013., Raleigh, North Carolina. Retrieved from https://catalog.lib.ncsu.edu/catalog/NCSU3085189

Rousseaux, S., Diguta, C. F., Radoï-Matei, F., Alexandre, H., & Guilloux-Bénatier, M. (2014). Non-Botrytis grape-rotting fungi responsible for earthy and moldy off-flavors and mycotoxins. *Food Microbiology*, *38*, 104–121.

Saldana, G., & Meyer, R. (1981). Effects of Added Calcium on Texture and Quality of Canned Jalapeno Peppers. *Journal of Food Science*, *46*(5), 1518–1520.

Scoville, W. L. (1912). Note on capsicums. *Journal of the American Pharmaceutical Association*, *1*(5), 453–454.

Sharma, C., Chambers, E., Jayanty, S. S., Rajakalyan, V. S., Holm, D. G., & Talavera, M. (2020). Development of a lexicon to describe the sensory characteristics of a wide variety of potato cultivars. *Journal of Sensory Studies*, *35*(4), e12577.

Smoley, R. (2020). Chile pepper acreage in steep decline. *Blue Book Services*. Marketing information for the produce industry, . Retrieved February 20, 2022, from https://www.producebluebook.com/2020/07/06/chile-pepper-acreage-in-steep-decline/

Statista. (2022, January). World vegetable production in 2020, by type. *Statista*. Retrieved February 20, 2022, from https://www.statista.com/statistics/264065/global-production-of-vegetables-by-type/

Stone, H., Sidel, J., Oliver, S., Woolsey, A., & Singleton, R. C. (2004). Sensory Evaluation by Quantitative Descriptive Analysis. *Descriptive Sensory Analysis in Practice* (pp. 23–34). John Wiley & Sons, Ltd. Retrieved March 10, 2022, from http://onlinelibrary.wiley.com/doi/abs/10.1002/9780470385036.ch1c

Suwonsichon, S., Iv, E. C., Kongpensook, V., & Oupadissakoon, C. (2012). Sensory lexicon for mango as affected by cultivars and stages of ripeness. *Journal of Sensory Studies*, *27*(3), 148–160.

Talavera-Bianchi, M., Chambers IV, E., & Chambers, D. H. (2010). Lexicon to describe flavor of fresh leafy vegetables. *Journal of Sensory Studies*, *25*(2), 163–183.

USDA ERS. (2021). *Peppers: U.S. Imports and Exports*. Retrieved February 20, 2022, from https://data.ers.usda.gov/reports.aspx?programArea=veg&top=5&HardCopy=True&RowsPerPage=25&groupName=Vegetables&commodityName=Peppers&ID=17858#Pa5d1706542ad4f35a0970703e84b0467_7_203

USDA NASS. (2021). *National Statistics for Peppers*. USDA National Agricultural Statistics Service. Retrieved February 20, 2022, from https://www.nass.usda.gov/Statistics_by_Subject/result.php?230D93B0-0322-3B03-B6EA-5FEA524F32B2&sector=CROPS&group=VEGETABLES&comm=PEPPERS

Ward, C. (2016). Some like it hot! Sensory analysis of products containing chemesthetic compounds. *Chemesthesis* (pp. 166–184). John Wiley & Sons, Ltd. Retrieved August 26, 2021, from https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118951620.ch10

Xiao, Z. B., Zhu, J. C., Feng, T., Tian, H. X., Yu, H. Y., Niu, Y. W., & Zhang, X. M. (2010). Comparison of volatile components in Chinese traditional pickled peppers using HS–SPME–GC–MS, GC–O and multivariate analysis. *Natural Product Research*, *24*(20), 1939–1953. Taylor & Francis.

Yang, G., Chambers, E., & Wang, H. (2021). Flavor lexicon development (in English and Chinese) and descriptive analysis of Sichuan pepper. *Journal of Sensory Studies*, *36*(2), e12636.

APPENDICES

A1. ACIDIFICATION RATE OF RED BELL PEPPERS

A1.1. Introduction

The acidification rate of red bell peppers influences the total processing time. It is an important consideration when designing a new process, especially when using microwaves as the uniformity of heating is highly dependent on the composition of the product.

A1.2. Materials and methods

Red bell peppers (n=18) were rinsed in tap water and sliced into rings of 6 mm thickness using a mandolin slicer. These rings were further cut into strips of 4 cm length. Brine with 0.37 M acetic acid (200 grain vinegar; commercial processor) and 0.76 M sodium chloride (purity ≥99.5%; Sigma Aldrich S-7653) was prepared. Red bell peppers and brine were combined in glass jars in a 55:45 ratio by volume. The peppers and brine were allowed to equilibrate at ambient temperature (~20°C). To determine the time taken for attaining equilibrium, the pH, titratable acidity, and sodium chloride concentration was measured at 0 h, 10 min (0.17 h), 20 min (0.33 h), 2 h, 4 h, 6 h, 12 h, 18 h and 24 h. Two jars were sampled for analyses at every time point.

The red bell pepper slices and brine in each of the jars were separated by decanting the brine. The red bell peppers were homogenized in a Waring blender set at speed 4.5 for 1 min. The homogenate was strained through a cheesecloth to obtain a filtrate (henceforth referred to as pepper filtrate) for analyses. On the other hand, the decanted brine was directly subjected to analyses. pH was measured using a calibrated (slope = 98.8%) Accumet 13-620-183A electrode connected to an Accumet XL500 (Fisher Scientific) pH meter.

Titratable acidity: The brine samples were titrated against 0.1N NaOH with continuous stirring to a pale pink end point that lasted at least for 30 s. Two drops of 1% phenolphthalein was used as the indicator. Since the pepper filtrate samples were highly colored, these were titrated potentiometrically to an end point of pH 8.2 which signifies the pH at which all the acid is neutralized. Samples of 10 ml diluted with 40 ml of neutralized water were used for titration. The ml of sodium hydroxide consumed was multiplied with a factor of 0.0601 to determine the titratable acidity as % acetic acid (Nielsen, 2019; Péréz-Diáz et al., 2013).

Sodium chloride concentration: The NaCl content in brine and pepper filtrate samples was determined by adopting a modified version of the Fajans method (Fajans & Hassel, 1923). Sample (1ml) was diluted with 20 ml of deionized water and titrated against 0.171 N Silver nitrate to a salmon pink end point using four drops of 0.5% dichlorofluroescein indicator. Constant stirring was important to break up the white precipitate formed during the titration. The ml of silver nitrate consumed was equivalent to the grams of NaCl in 100 ml of sample (Fleming, McFeeters, & Breidt, 2001; McMurtrie & Johanningsmeier, 2018; Pérez-Díaz et al., 2013).

A1.3. Results and Discussion

The pH, titratable acidities, and sodium chloride concentrations of brine and pepper filtrate samples at different acidification times at ambient temperature are summarized in Table A1. After 24h of acidification, red bell peppers had a pH of 3.5±0.02, titratable acidity of 1.1±0.01% (as acetic acid), and 1.8±0.21 g NaCl per 100 ml. The differences between brines and pepper filtrates at different acidification times revealed that the difference in pH did not change significantly ($p>0.05$) beyond 6 h (Figure A1.a). The difference in titratable acidity (Figure A1.c) and sodium chloride concentration (Figure A2.d) did not change significantly ($p>0.05$) beyond 4 h. pH is the negative log transformation of hydrogen ion concentration in a solution. When the

hydrogen ion concentration [H^+] was modeled against acidification time instead of pH, the difference between the brines and pepper filtrates did not change beyond 4 h of acidification time (Figure A1.b), which was consistent with the differences in titratable acidity and sodium chloride concentration.

Table A1 Summary of pH, titratable acidity, and sodium chloride concentrations in brines and pepper filtrates at various acidification times. ND = Not detected. Same superscript letters within a column indicate no significant difference ($p>0.05$) among acidification times.

Time (h)	Mean pH		Titratable acidity (% acetic acid)		Sodium chloride (g per 100 ml)	
	Brine	Pepper filtrate	Brine	Pepper filtrate	Brine	Pepper filtrate
0	2.42± 0.01^{e}	5.175±0.05^{a}	2.2988±0.10^{a}	0.1503±0.00^{d}	4±0.00^{a}	ND^{d}
0.17	3.1±0.00^{d}	3.945±0.01^{b}	1.6437±0.004^{b}	0.6791±0.03^{c}	3.1±0.00^{b}	0.85±0.07^{c}
0.33	3.125±0.02^{d}	3.925±0.04^{b}	1.5836±0.04^{b}	0.6761±0.06^{c}	2.95±0.07^{bc}	0.9±0.00^{c}
2	3.28±0.04^{c}	3.695±0.04^{c}	1.2982±0.05^{c}	0.9376±0.04^{b}	2.65±0.07^{c}	1.5±0.14^{b}
4	3.415±0.01^{b}	3.575±0.01^{cd}	1.1539±0.00^{c}	1.0638±0.01^{a}	2.3±0.14^{d}	1.75±0.21^{ab}
6	3.48±0.00^{ab}	3.595±0.02^{d}	1.1569±0.04^{c}	1.0818±0.01^{a}	2.05±0.07^{de}	1.55±0.07^{ab}
12	3.485±0.01^{ab}	3.505±0.01^{d}	1.1449±0.004^{c}	1.1419±0.00^{a}	2±0.14^{de}	1.6±0.14^{ab}
18	3.49±0.01^{a}	3.51±0.01^{d}	1.1449±0.04^{c}	1.1359±0.01^{a}	1.95±0.07^{e}	2.1±0.00^{a}
24	3.495±0.02^{a}	3.495±0.02^{d}	1.1479±0.00^{c}	1.0908±0.01^{a}	1.95±0.07^{e}	1.75±0.21^{ab}

The time required to achieve equilibrium i.e., 4 h, may not ensure inhibition of pathogens such as *Escherichia coli* O157:H7, which was inactivated up to 5 logs CFU/ml after 30 h at 25°C in acidified cucumbers (Breidt, Hayes, & McFeeters, 2007), which represents the worst case scenario due to lack of any known inhibitory compounds in cucumbers. However, microbiological inactivation can be addressed by pasteurization that also renders products to be

stable at ambient conditions. Dielectric properties are known to be influenced by the chemical composition of food. The results obtained in this study are likely to be consistent with no significant differences in dielectric properties between 4 h and 24 h soaking of red bell peppers in brine found by Koskiniemi, Truong, McFeeters, & Simunovic, (2012). Food with uniform chemical composition enables uniform heat distribution in a multiphase product such as acidified peppers, and faster heating rates to maximize quality retention. With regards to process design, the information on acidification rate is useful in developing an efficient and sustainable process, such as the incorporation of vacuum impregnation to increase acidification rates and avoiding any compromise on safety or delays in processing time.

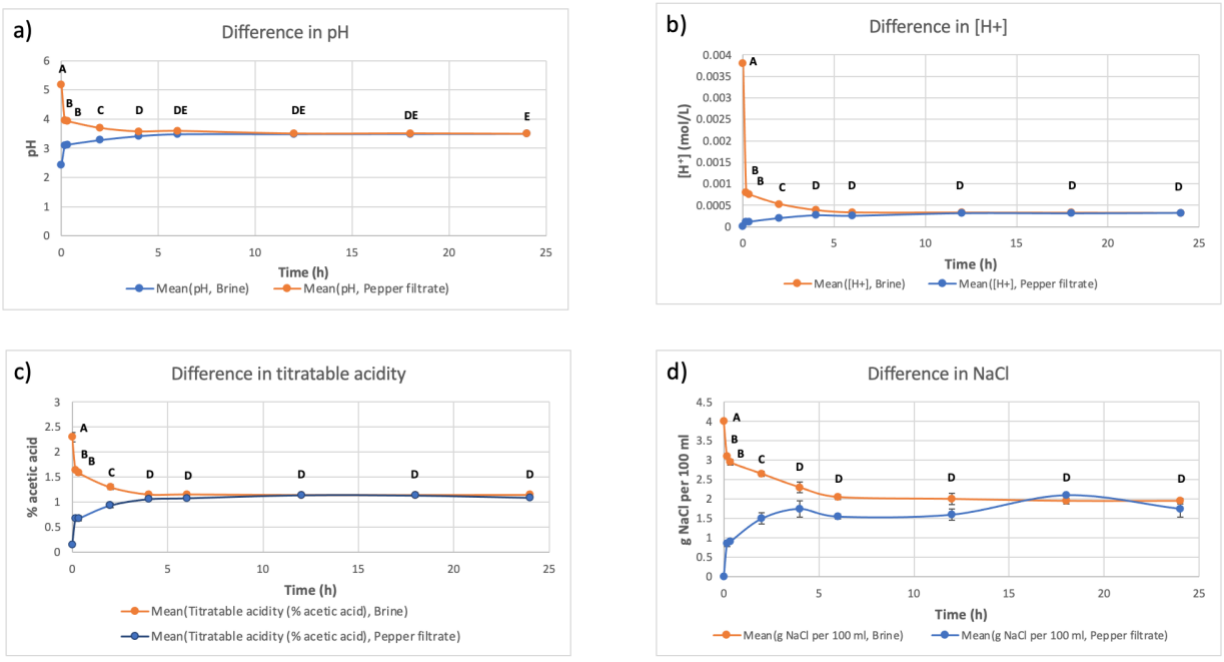

Figure A1 Difference in pH (a), hydrogen ion concentration (b), titratable acidity as % acetic acid (c), and sodium chloride concentration (d) between brines and pepper filtrates at various acidification times. Same letters indicate no significant change ($p>0.05$) in the difference between brine and pepper filtrate. Error bars denote the standard deviation that may too small to be visible.

A2. MEASUREMENT OF PH OF ACIDIFIED RED BELL PEPPER HOMOGENATES WITH DIFFERENT COMPOSITIONS

A2.1. Introduction

The chemical properties such as pH and salt concentrations of acidified red bell peppers of varying compositions is useful in determining the thermal processing requirements (Breidt et al., 2014, Breidt et al., 2013) for ensuring safety. Such information is also useful in guiding product formulation. Knowledge of the chemical properties across different compositions also makes data available for statistical modeling that can enable prediction of such properties.

A2.2. Method

The red bell pepper homogenates were tested for pH and sodium concentration using a potentiometer (Accumet XL 500, Fisher Scientific). Both electrodes were calibrated before commencing measurement. The Accumet 13-620-183A (Fisher Scientific) pH electrode was calibrated with pH 7.00, 4.01 and 2.00 buffers, resulting in a slope of 98.5%/58.3mV. A similar electrode that could select for sodium ion (Accumet 13-620-503, Fisher Scientific) was sequentially calibrated with 0.01 M, 0.1 M and 1M sodium chloride solutions containing 2 ml ion selective adjuster (Fisher Scientific ACCU0832500) for every 100 ml. An acceptable slope of 56.1 mV was obtained (acceptable range: 54-60 mV), that translates to R2=95.8%. This ion selective electrode yielded sodium concentrations in mol/L. The pH and sodium concentrations were measured at 25°C (sample temperature). Automatic temperature compensation was applied for all the measurements.

A2.3. Results

The results of pH and sodium concentration (mol/L) have been tabulated in Table A2. As expected, the pH decreased with increase in acetic acid concentration. The measured sodium concentration increased with the salt content added to samples. However, the variance in such a measurement was not similar across different levels of added salt. The high average error (0.64) could be because of the lower pH of these samples outside of the optimum range (pH 5 – 12).

Table A2 Summary of pH and sodium concentrations of various formulations of red bell pepper homogenates

	Acetic acid (%)	**NaCl (%)**	**Lot**	**pH**	**Sodium (mol/L)**
1	0	0	1	5.14	0.016
2	0.5	0	1	4.00	0.013
3	1	0	1	3.74	0.014
4	2	0	1	3.47	0.017
5	4	0	1	3.23	0.032
6	0	1	1	4.86	0.157
7	0.5	1	1	3.71	0.202
8	1	1	1	3.52	0.164
9	2	1	1	3.21	0.180
10	4	1	1	2.96	0.245
11	0	2	1	4.74	0.267
12	0.5	2	1	3.72	0.504
13	1	2	1	3.60	0.569
14	1	2	2	3.49	0.534
15	1	2	3	3.37	0.856
16	2	2	1	3.20	0.841
17	4	2	1	3.00	0.779
18	0	4	1	4.63	0.888
19	0.5	4	1	3.51	1.249
20	1	4	1	-	-
21	2	4	1	3.00	1.236
22	4	4	1	3.02	1.429

APPENDIX 3: DETERMINATION OF POLYGALACTURONASE ACTIVITY IN FRESH RED BELL PEPPERS

A3.1. Introduction

Texture of fresh produce is principally governed by the structure and composition of the primary cell wall and middle lamella in the plant cellular structure. Typically, increased solubilization of pectic substances and loss of cell wall galactose occur during ripening and softening of fruits and vegetables. Main reason behind this is the action of hydrolytic enzymes on cell wall materials (Van Buren, 1979).

Bell peppers (*Capsicum annuum*) are non-climacteric and a part of the *Solanacaea* family along with tomatoes, potatoes, and eggplants. They are widely consumed globally, and are known to be rich in ascorbic acid (Zhang & Hamauzu, 2003). Although there is considerable research on the cell wall changes occurring in tomatoes, there is little work done on bell peppers probably because the enzyme activities are 100-150 times lower (Jen & Robinson, 1984). As bell peppers ripen, one of the many biochemical changes occurring is the increase in polygalacturonase (PG) activity. Red bell peppers, which are the mature fruits of green bell peppers, are reported to have the highest activity (Ahmed et al., 2011; Jen & Robinson, 1984; Liu et al., 2015; Sethu, Prabha, & Tharanathan, 1996) and potentially the most heat stable form of PG (Jen & Robinson, 1984) compared to immature fruits. Jen & Robinson (1984) also speculated that PG occurs in two isozyme forms in red bell peppers supported by the existence of two pH optima (4.8-5.0 and 5.5-6.0). PG is known to be the cause of softening in numerous non-climacteric fresh (Andrews & Li, 1995; Cabanne & Donèche, 2001; Chea et al., 2019; Xin et al., 2021) and acidified fruits and vegetables (Bell, Etchells, & Jones, 1950; Cho & Buescher, 2012; McFeeters, Bell, & Fleming, 1980) such as cherries, grapes, blueberries, and cucumbers. While

pectin methylesterase (PME) is also active in bell peppers, Sethu et al., (1996) reported that its activity subsides as fruits mature into red bell peppers. This hints the fact that PME is likely not involved in softening of bell pepper after reaching maturity. Other cell-wall degrading enzymes such as cellulase (Rao, Gol, & Shah, 2011), beta galactosidase II, and mannosidase (Ogasawara, Abe, & Nakajima, 2007; Prabha, Neelwarne, & Tharanathan, 1998; Sethu et al., 1996) are also known to be active in mature fruits of bell pepper. Besides occurring naturally, softening enzymes such as PG in bell peppers could also be from fungal sources, most commonly *Botrytis cinerea* (Johnston & Williamson, 1992; Poverenov et al., 2014). As a starting point to addressing the softening issues occurring in acidified red bell peppers, investigation on the thermal inactivation of PG will provide the basis for determining the target temperature and holding time for the microwave processing.

Most commonly, vegetable products are heat processed to extend their shelf life. The inactivation of PG by heat can be characterized by its D and z_c values. Knowledge of the thermal inactivation kinetics are useful for designing processes. D value is the decimal reduction time i.e., in this context, the time taken for the enzyme activity to be reduced by 1 log at a given temperature. The temperature change required for a 1 log change in the D value of the enzyme is given by z_c value. By knowing these two quantities, the calculation of cook value (C value) given in Eq. (A1) makes it possible to arrive at various time-temperature combinations to achieve a desired level of enzyme inactivation.

$$C = 10^{\frac{T-T_{ref}}{z_c}} \Delta t \qquad \text{Eq. (A1)}$$

So far, the thermal inactivation kinetics of red bell pepper PG have not been established, but an early study quoted complete inactivation at 60°C for 20 min (Jen & Robinson, 1984), which can only be considered as an indicative value as the method used is unknown. It may also be useful to note that PG activity could be influenced by the pH (Anthon, Sekine, Watanabe, & Barrett, 2002) and sodium chloride (Pressey, 1986), as seen in the case of tomatoes. Thus, it will be useful to determine the kinetics of fresh and acidified red bell peppers.

In order to determine the D and z_c values of PG in fresh and acidified red bell peppers, representative samples need to be processed isothermally at various temperatures for specific holding times. The PG activity before and after processing at these conditions need to be analyzed. PG activity (on a log scale) plotted against holding times gives a slope that is equal to $-1/D_T$ at a particular temperature T. When the D value (on log scale) is plotted against temperature, the slope is equal to $-1/z_c$.

Before investigating the inactivation kinetics, determining the PG activity in fresh red bell peppers will give an idea about the highest activity one can expect and the detection range required.

A3.2. Materials and Methods

A3.2.1. Preparation of slurry

Red bell peppers (4 fruits) were purchased from the local market. These peppers were labeled as green house-grown in Mexico. These were rinsed under tap water, towel-dried, and cut into strips of 1 cm x 2.5 cm. The strips were ground in a Waring blender for 1 min at speed 3, 3 min at speed 4, and 3 min at speed 5 sequentially to a slurry. The puree was stirred at 4°C for

20 min at 800 rpm to make it a homogenous sample. One part of this slurry was frozen at -80°C for 1.5 h, while the other part was kept in a refrigerator (4°C) for the interim.

A3.2.2. Enzyme extraction

To assess the effect of extraction conditions on polygalacturonase activity, three different slurry quantities (2.5 g, 3.75 g, and 5 g) and a freezing step before homogenization with NaCl were studied. The frozen slurry was thawed till it appeared as a slurry (which had a temperature around 4°C). The chilled slurry was taken out of the refrigerator. Aliquots of 2.5 g, 3.75 g, and 5g were taken in 50 ml conical tubes (Fisher Scientific cat# 14-955-239). Double the volume of 2M NaCl solution was added to the slurry, which was then homogenized at 16,000 rpm for 1 min using Ika T25 Ultra-Turrax homogenizer with the S25N-25G dispersion tool. The slurries were incubated at 4°C with stirring at 300 rpm for 1 h for extracting the enzyme from the plant tissue. The crude extract thus obtained was directly subjected to the enzyme assay (described in A3.2.3). The crude extract was also further purified to a crude concentrate by taking 4ml in an Amicon Ultra-4 centrifugal filter, which was centrifuged at 7197xg for 20 min at 4°C. Care was taken to always choose filtering membranes with low protein binding. Another method of purification of the crude extract was done by centrifuging at 12,000 rpm for 20 min at 4°C to remove cellular material. The supernatant (4 ml) was taken in a centrifuge tube (Fisher Scientific, cat# 3118-0010) to which 2.13 g of $(NH_4)_2SO_4$ was added to reach at least 80% saturation. The tubes were vortexed for 30 s and centrifuged at 4°C at 15,000 rpm for 20 min. The supernatant was discarded, and the residual pellet was suspended in 150 μL of 80 mM acetate buffer pH 5.5. Such an enzyme extract has been referred to as the precipitated extract henceforth. The schematic diagram of the enzyme extraction processes is given in Figure A2.

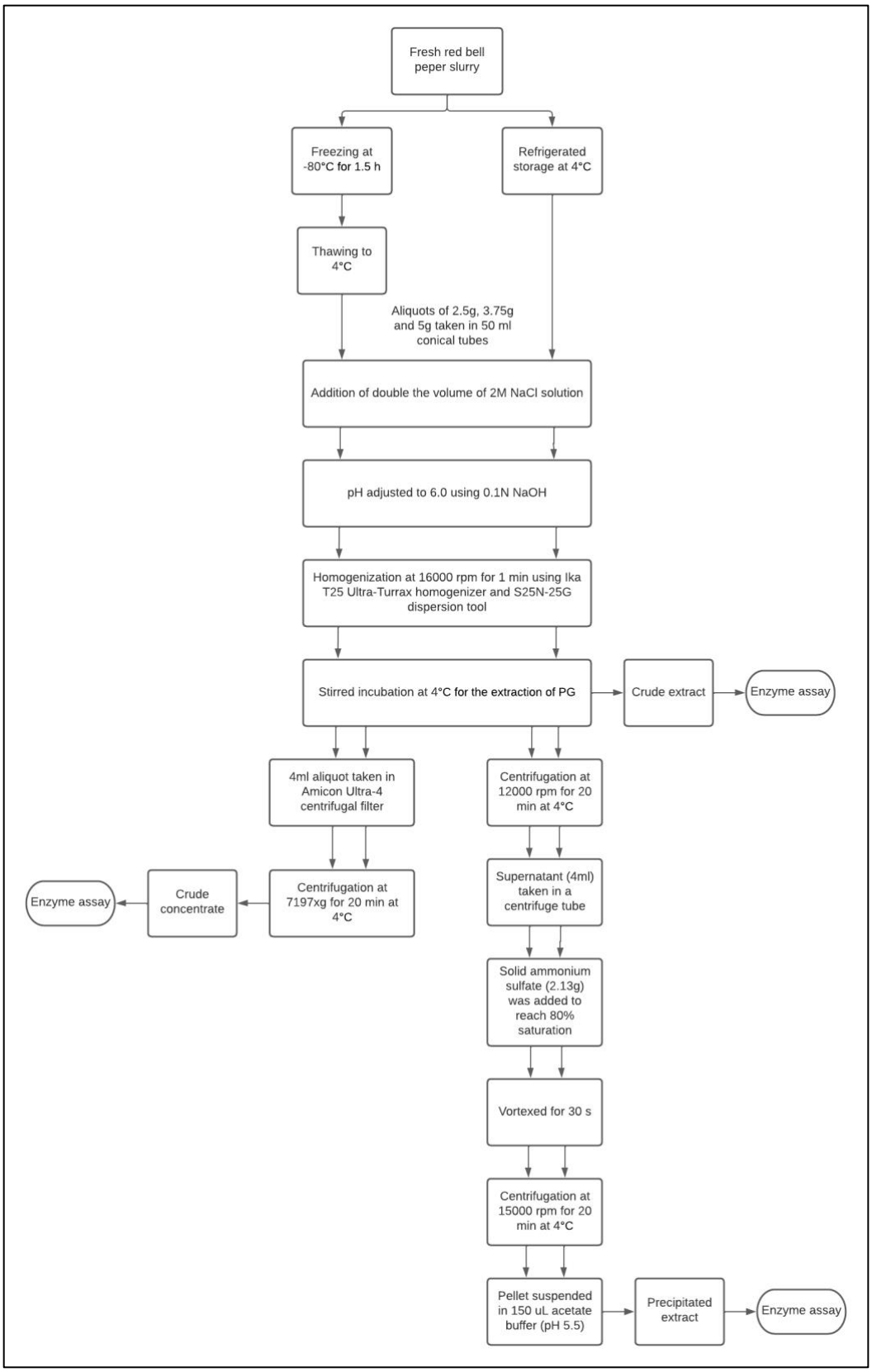

Figure A2 Polygalacturonase extraction processes investigated in this study.

A3.2.3. Enzyme assay

A colorimetric assay for determining polygalacturonase activity was adapted from Torres, Sayago, Ordoñez, & Isla (2011). Down-sizing the assay from a cuvette to a microplate was found to have similar variation but much lower processing times. This was determined experimentally and supported by the work of Ortiz, Guitart, Albertó, Fernández Lahore, & Blasco (2014). The steps in the colorimetric assay are represented in the form of a flowchart in Figure A2. To study the influence of assay conditions on the polygalacturonase activity, two substrate concentrations (0.05% and 0.187%) and two enzyme volumes (2.5 uL and 7.5 uL) were investigated. Incubation time of 48 h was chosen as lower reaction times (20 min, 40 min, 2 h, 4 h, 6 h, 12 h and 24 h) did not result in detecting any enzyme activities. This incubation time is also consistent with the widely used diffusion plate assay for determining polygalacturonase activity (Buescher & Burgin, 1992). It is important to note that the concentration of ruthenium red added is equal to the initial concentration of the polygalacturonic acid (PGA) substrate. So, if a lower concentration of PGA substrate is used at the beginning of the assay, the dosage of ruthenium red added to the assay is equivalent. This is to ensure that zero absorbance is obtained when PGA has not been hydrolyzed (or when there is no enzyme activity). Standard calibration curves of absorbance of different concentrations of polygalacturonic acid (PGA) ranging from 0% to 0.05% (curve 1) and 0% to 0.187% w/v (curve 2) were obtained to establish the direct relation between absorbance and concentration of unhydrolyzed PGA. The concentration of unhydrolyzed PGA is inversely related to the enzyme activity. Higher the enzyme activity, lower the concentration of unhydrolyzed PGA and higher the absorbance of supernatant. The enzyme activity unit is defined as the amount of enzyme required to hydrolyze 1 ug of PGA in smaller fragments unable to bind the dye per minute per unit volume of enzyme extract under the assay

conditions. To test if the method is working, commercially available polygalacturonase standard (sourced from *Aspergillus flavus*) at different concentrations was assayed.

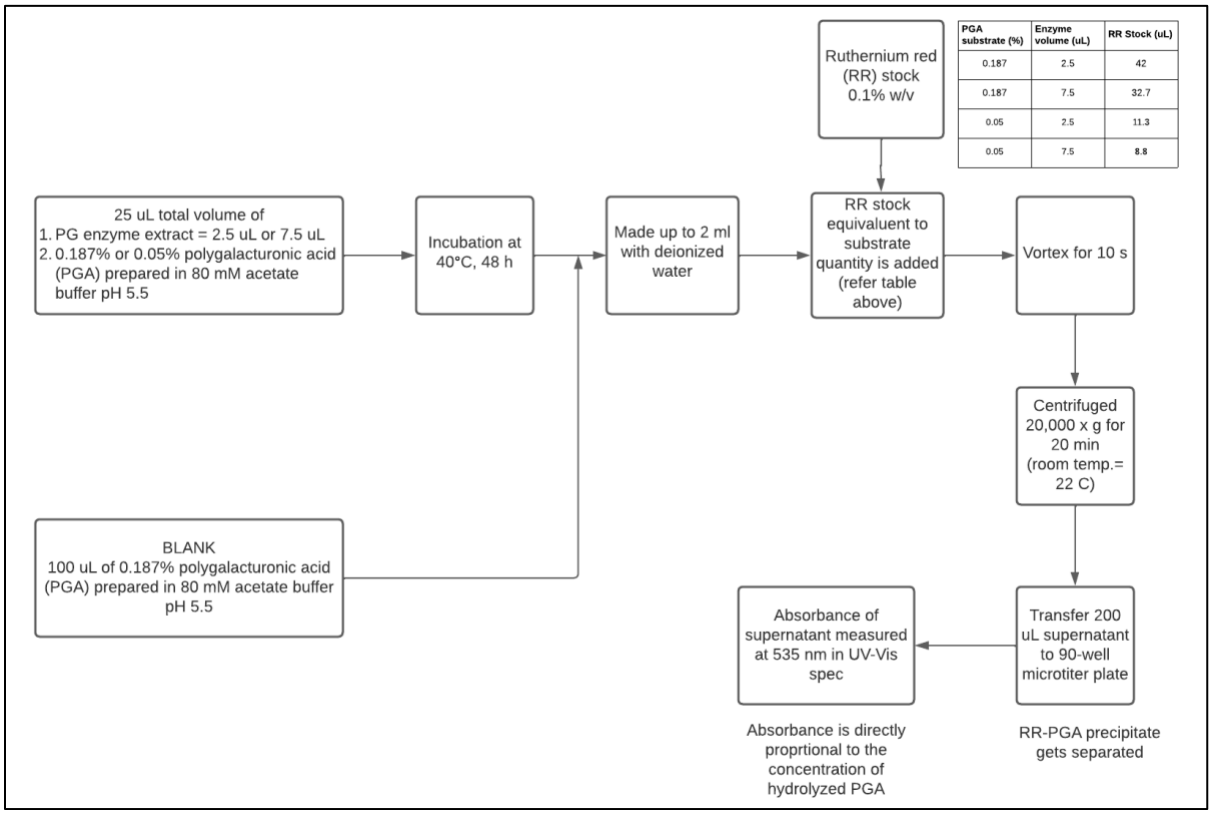

Figure A3 Microplate method for colorimetric assay of polygalacturonase activity.

The slopes of the standard calibration curves were used to calculate PG activities; curve 1 was used to calculate the activity when the 0.05% PGA substrate was tested, while curve 2 was used when 0.187% PGA substrate was tested. PG activities were calculated using the formula (Ortiz et al., 2014) –

$$PG\ activity\ (\mu g\ min^{-1} ml^{-1}) = \frac{SB - SA}{SLP\ x\ t\ x\ V}$$

SB – Absorbance of blank

SA – Absorbance of sample

SLP – Least squares slope of calibration curve

t – Reaction time (= 20 min in this experiment)

V – volume (ml) of enzyme extract used per reaction (= 10uL in this experiment)

A3.2.4. Thermal processing trials

Pouches (2.55 in width x 3.35 in height) filled with 5g slurry were thermally processed in an oil bath (Model RTE111, Neslab Instruments Inc, Newington, NH) at temperatures from 60°C to 100°C. The temperatures were recorded by thermocouples (type T) connected to a digital display (Digi-sense data logging thermocouple meter 20250-92) and the come-up times were noted.

A3.3. Results and Discussion

The standard calibration curves obtained are depicted in Figures A4 and A5. It has a negative slope because a lower degree of hydrolysis of PGA (or higher concentration of unhydrolyzed PGA) is bound to result in the supernatant having a lower absorbance. The range of absorbances in Figure A5 is higher because a higher concentration of ruthenium red was added equivalent to the higher substrate concentration.

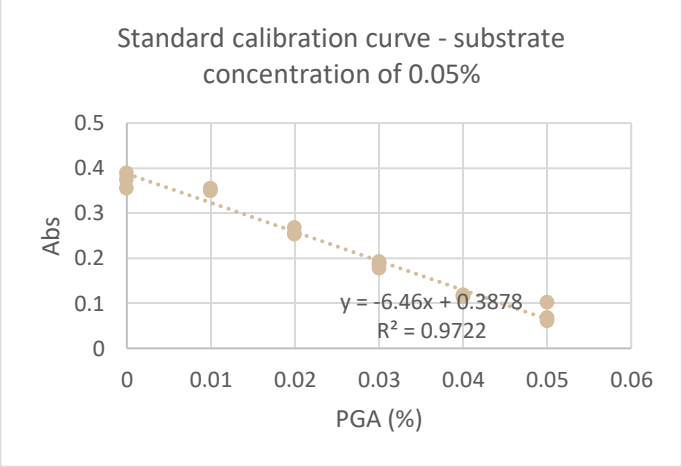

Figure A4 Standard calibration curve for substrate concentration of 0.05% PGA.

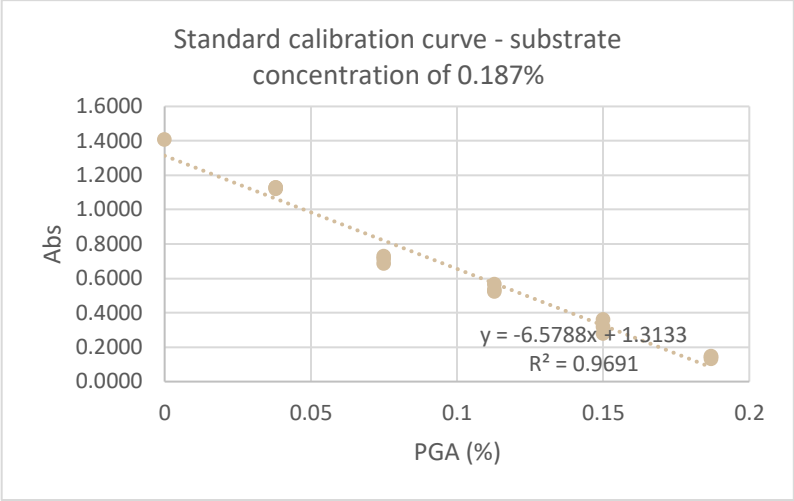

Figure A5 Standard calibration curve for substrate concentration of 0.187% PGA.

Figure A6 shows the performance of the colorimetric assay with known PG standards. Mean activities reduced as the enzyme concentrations increased. Enzyme volume (2.5 µL) significantly increased the activity, but the substrate concentration did not influence the activity significantly ($p>0.05$). Typically, the reaction rate of an enzyme is known to increase with concentration, but the results here indicate the opposite with large variation within each treatment. Comparatively, the diffusion plate assay (Buescher & Burgin, 1992) has higher sensitivity at the tested enzyme concentrations and can show sizeable differences up to enzyme concentrations of 2.1×10^{-4} U/ml above which the increases in activity are smaller. Although the works of Torres et al. (2011) and Ortiz et al. (2014) from which this colorimetric assay was adapted, used a PG standard to validate their method, these studies did not compare the effect of different enzyme concentrations on the activities.

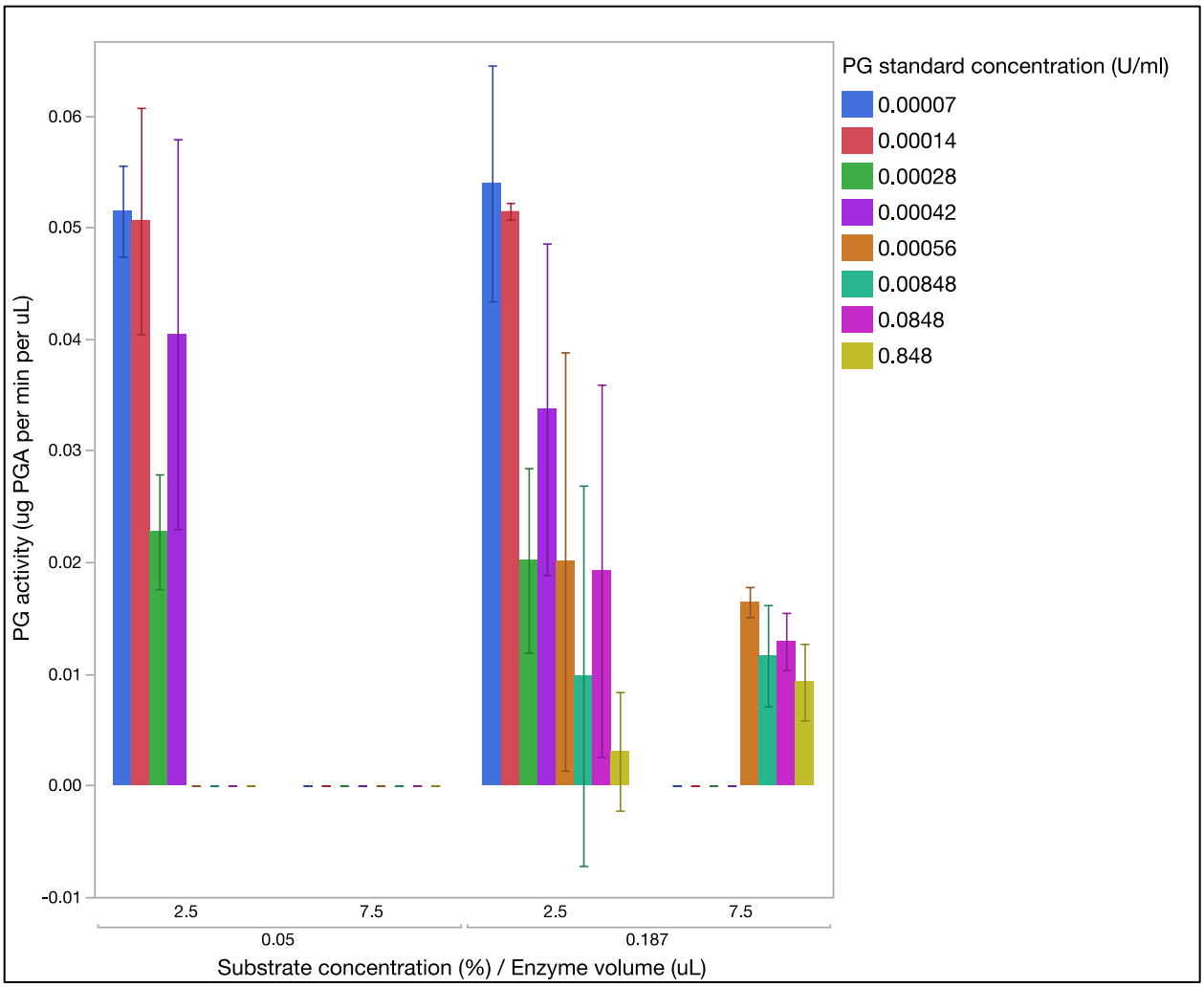

Figure A6 Mean polygalaturonase activities in standard solutions.

The PG activities detected in fresh red bell peppers as crude extract and crude concentrate were higher than the PG standards. However, when the corresponding absorbance values were positioned on the standard calibration curve, these were still at the lower end. The effects of slurry quantity and freezing before homogenization were not significant ($p>0.05$) on the PG activity, while the enzyme volume (2.5 µL) and substrate concentration (0.187%) caused significant increases in PG activity (compared to other enzyme volumes and substrate concetrations investigated in this study).

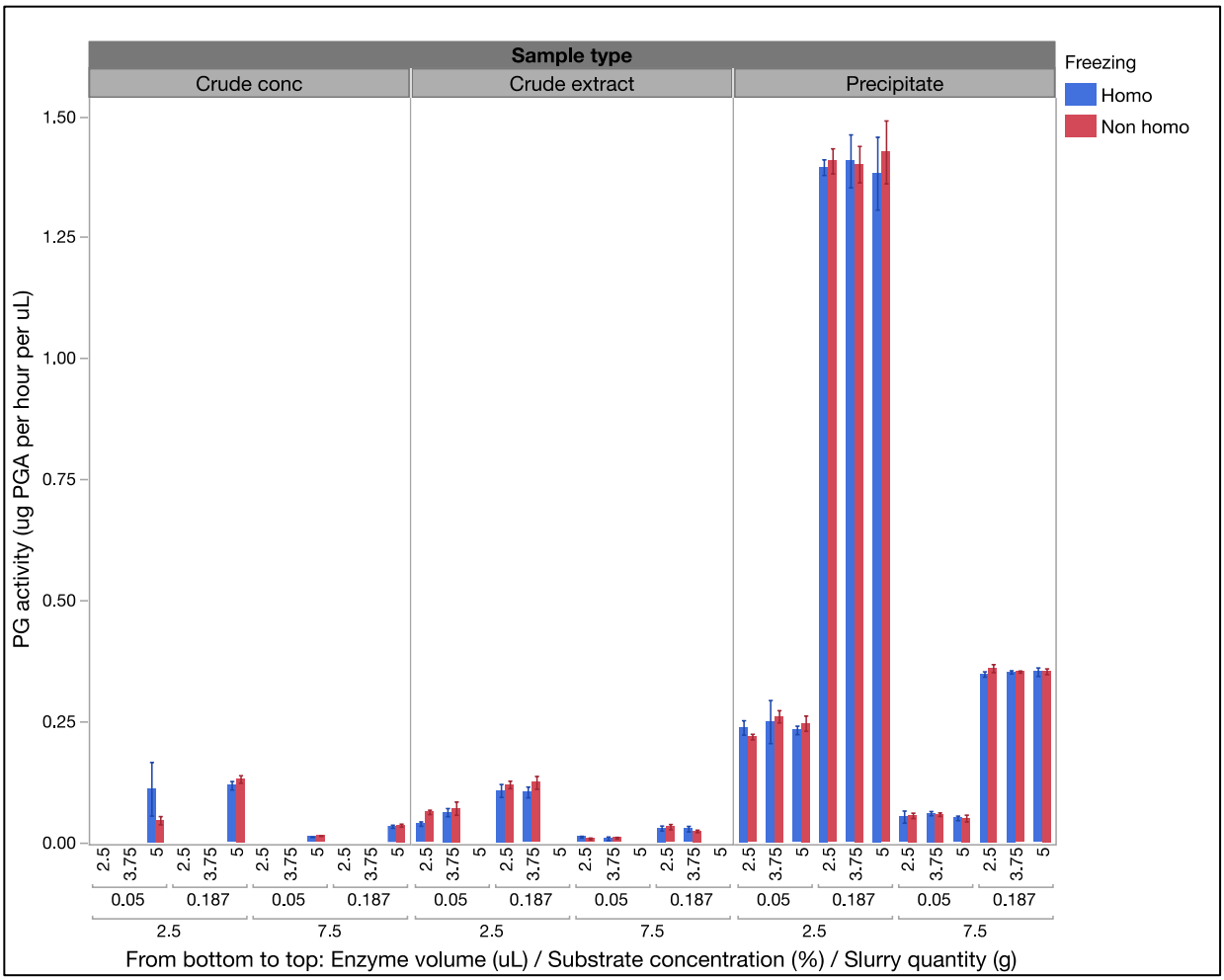

Figure A7 PG activities in crude extract, crude concentrate, and precipitated extract as effects of enzyme volume, substrate concentration, slurry quantity, and inclusion of a freeze-thaw cycle.

No significant difference was noted in the PG activities of crude extract and crude concentrate, which indicates that the centrifugal filter may not be significantly helping in concentrating the proteins. This was expected when clogging of the filter membrane was observed due to particulates in the crude extract. However, precipitated extracts incubated with 0.187% substrate was found to show much higher PG activities (Figure A7). Enzyme extract volume of 2.5 µL was found to be optimal to obtain absorbances (Figure A8) in the range 1.0-1.2, that corresponded with low level of unhydrolyzed PGA (or high degree of PGA hydrolysis) on the standard calibration curves (Figure A5). This is desirable when fresh red bell peppers are

intended to be thermally processed, which is expected to result in decrease in absorbance and PG activities. That way, a wide range of PG activities present in peppers processed at different temperature-time combination can be quantified. However, the consistency in PG activities in different lots of red bell peppers needs to be confirmed. It is recommended to obtain or screen fruits that are known to possess high PG activities (such as field-grown ones or softened lots from processors) to be able to study the PG thermal inactivation kinetics. It is also recommended to calculate PG activity from the absorbance of blank that is prepared by adding the enzyme extract but bypassing the incubation step (Ortiz et al., 2014). This will help in ignoring the effect of interfering substances in pepper on the absorbance. However, the effects of PG-inhibiting substances naturally present in pepper (Kalunke et al., 2015) fruits are not known through these experiments, and hence needs to be considered for optimizing PG extraction and assay protocols.

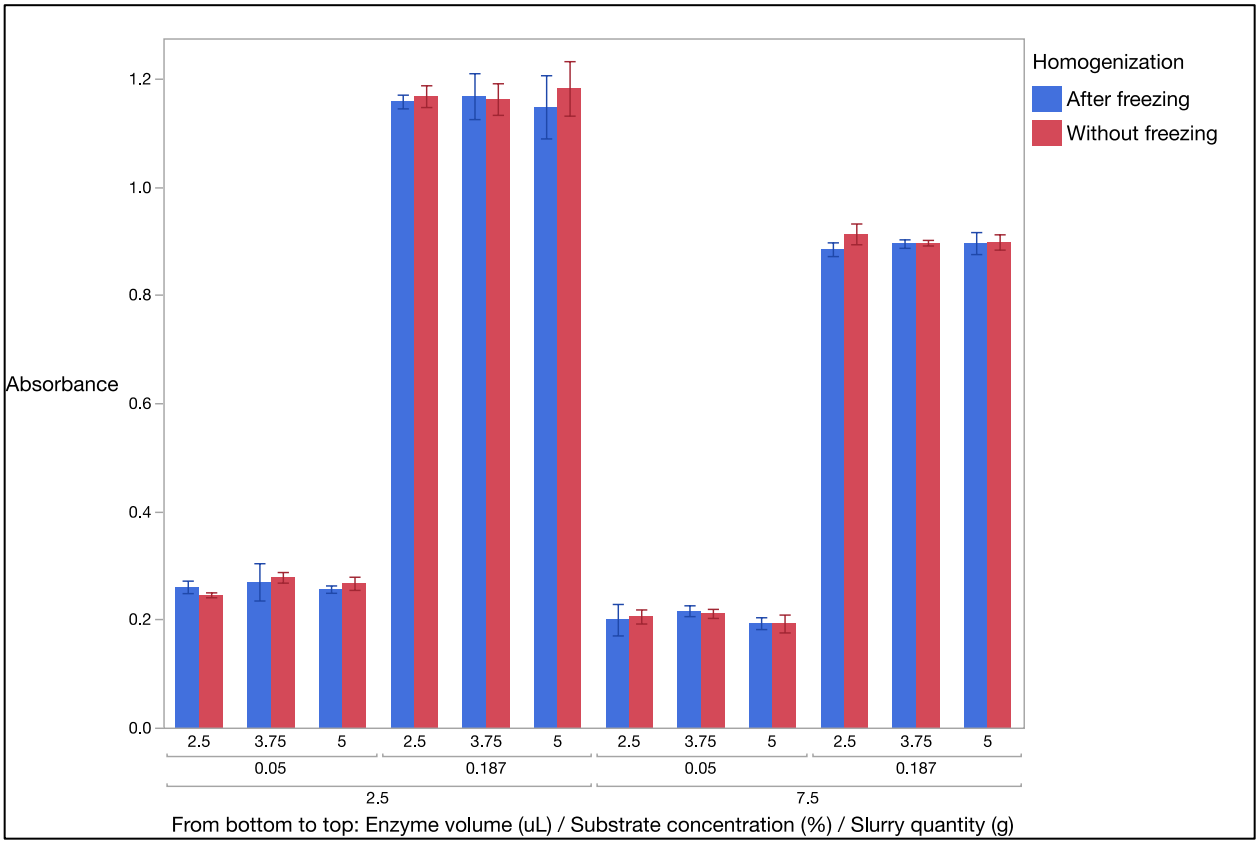

Figure A8 Absorbance of supernatants of reaction mixtures composed of precipitated extract.

Preliminary thermal processing trials revealed that the come-up times differed between different lots of red bell peppers and did not show a specific trend with respect to the target temperatures. The come-up times for two lots of red bell peppers are tabulated in Table A3. However, the come-up times decreased for both lots of peppers when the oil bath was set to 90°C. Such long come-up times are not favorable for studying thermal inactivation kinetics as the goal is to focus on the effects of various holding times by keeping come-up times as low as possible. Reducing the sample quantity and/or trying a different packaging material may address this. As observed earlier in Figure A8, no significant differences in PG activities among slurry quantities were noted and hence reduction in sample quantity is a potential solution. Earlier studies have been done using capillary tubes to maximize the rate of heat transfer and reduce the come-up times. A proposed experimental design of temperature-holding time combinations for studying the thermal inactivation kinetics of PG is presented in Figure A9.

Table A3 Come-up times for heating fresh red bell pepper slurries to temperatures 60°C to 100°C.

Temperature (°C)	**Come-up time (min) for lot 1**	**Come-up time (min) for lot 2**
60	7.5	5.6
70	7.0	6.2
80	8.5	2.4
90	5.5	3.0
100	9.5	6.0

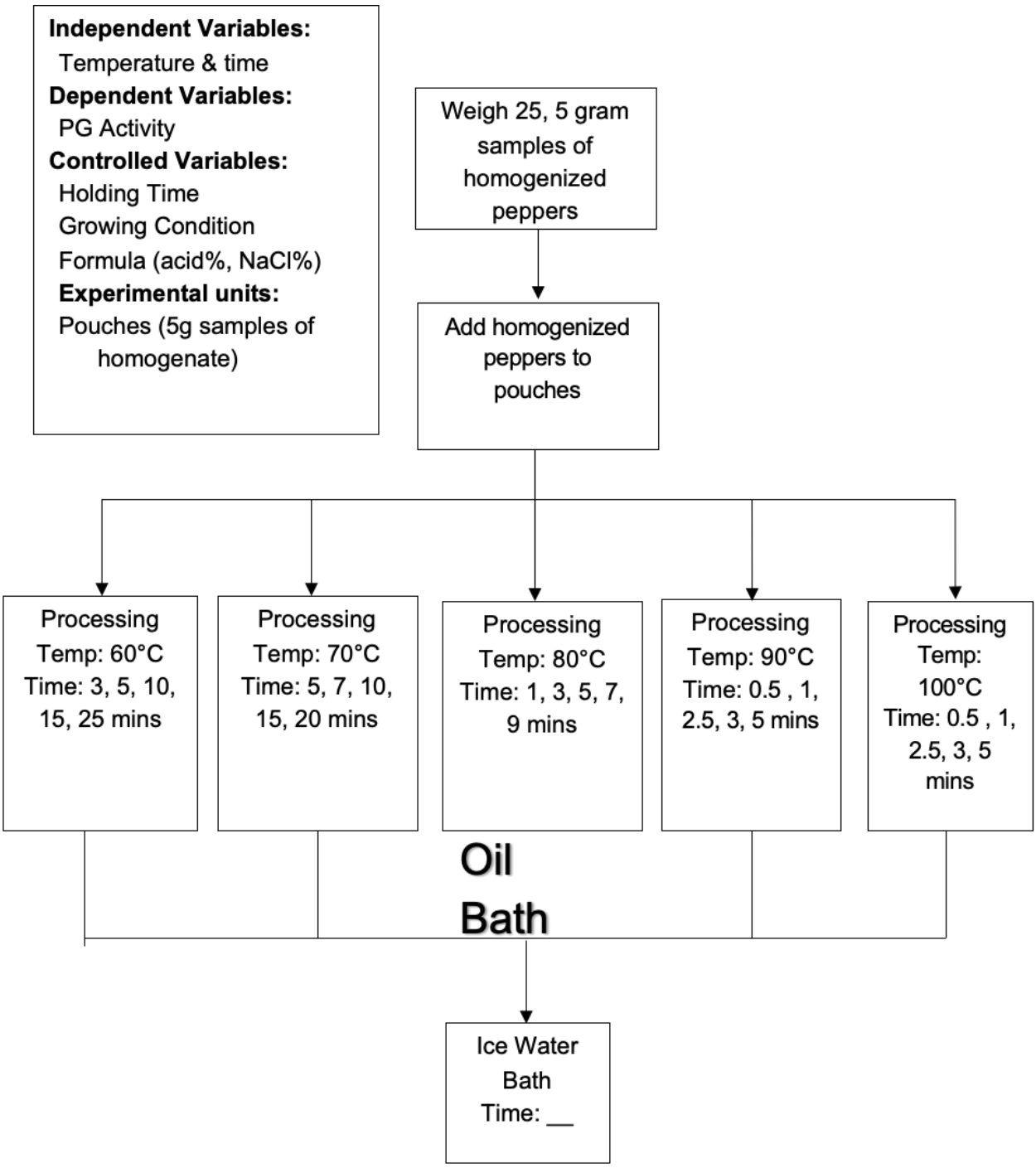

Figure A9 Proposed experimental design for studying the thermal inactivation kinetics of polygalacturonase.

REFERENCES

Ahmed, S. S., Gong, Z.-H., Khan, M. A., Yin, Y.-X., Guo, W.-L., & Imran, J. (2011). Activity and expression of polygalacturonase vary at different fruit ripening stages of sweet pepper cultivars. *Genetics and Molecular Research: GMR*, *10*(4), 3275–3290. https://doi.org/10.4238/2011.November.22.10

Andrews, P. K., & Li, S. (1995). Cell wall hydrolytic enzyme activity during development of nonclimacteric sweet cherry (Prunus avium L.) fruit. *Journal of Horticultural Science*, *70*(4), 561–567. https://doi.org/10.1080/14620316.1995.11515327

Anthon, G. E., Sekine, Y., Watanabe, N., & Barrett, D. M. (2002). Thermal Inactivation of Pectin Methylesterase, Polygalacturonase, and Peroxidase in Tomato Juice. *Journal of Agricultural and Food Chemistry*, *50*(21), 6153–6159. https://doi.org/10.1021/jf020462r

Breidt, F., Hayes, J., & McFeeters, R. F. (2007). Determination of 5-Log Reduction Times for Food Pathogens in Acidified Cucumbers during Storage at 10 and 25°C. *Journal of Food Protection*, *70*(11), 2638–2641. https://doi.org/10.4315/0362-028X-70.11.2638

Breidt, F., Kay, K., Cook, J., Osborne, J., Ingham, B., & Arritt, F. (2013). Determination of 5-Log Reduction Times for Escherichia coli O157:H7, Salmonella enterica, or Listeria monocytogenes in Acidified Foods with pH 3.5 or 3.8. *Journal of Food Protection*, *76*(7), 1245–1249. https://doi.org/10.4315/0362-028X.JFP-12-528

Breidt, F., Kay, K., Osborne, J., Ingham, B., & Arritt, F. (2014). Thermal Processing of Acidified Foods with pH 4.1 to pH 4.6. *Food Protection Trends*, *34*(2), 132–138. http://www.proquest.com/docview/1519532718/abstract/C7FB2AF544294E3DPQ/1

Buescher, R., & Burgin, C. (1992). Diffusion plate assay for measurement of polygalacturonase activities in pickle brines. *Journal of Food Biochemistry*, *16*, 59–68. https://doi.org/10.1111/j.1745-4514.1992.tb00433.x

Cabanne, C., & Donèche, B. (2001). Changes in Polygalacturonase Activity and Calcium Content during Ripening of Grape Berries. *American Journal of Enology and Viticulture*, *52*(4), 331–335. https://www.ajevonline.org/content/52/4/331

Chea, S., Yu, D. J., Park, J., Oh, H. D., Chung, S. W., & Lee, H. J. (2019). Fruit softening correlates with enzymatic and compositional changes in fruit cell wall during ripening in 'Bluecrop' highbush blueberries. *Scientia Horticulturae*, *245*, 163–170. https://doi.org/10.1016/j.scienta.2018.10.019

Cho, M. J., & Buescher, R. W. (2012). Potential Role of Native Pickling Cucumber Polygalacturonase in Softening of Fresh Pack Pickles. *Journal of Food Science*, *77*(4), C443–C447. https://doi.org/10.1111/j.1750-3841.2012.02649.x

Etchells, J. L., & Bell, T. A. (1950). Film yeasts on commercial cucumber brines. *Food Technology*, *4*, 77–83.

Fajans, K., & Hassel, O. (1923). A new method for titration of silver and halogen ions with organic dyestuff indicators. *Zeitschrift Fu¨r Elektrochemie Und Angewandte Physikalische Chemie*, *29*, 495–500.

Fleming, H., McFeeters, R., & Breidt, F. (2001). *Fermented and Acidified Vegetables* (pp. 521–532). American Public Health Association.

Jen, J. J., & Robinson, M. L. (1984). Pectolytic Enzymes in Sweet Bell Peppers (Capsicum annuum L.). *Journal of Food Science*, *49*(4), 1085–1087. https://doi.org/https://doi.org/10.1111/j.1365-2621.1984.tb10398.x

Johnston, D. J., & Williamson, B. (1992). Purification and characterization of four polygalacturonases from Botrytis cinerea. *Mycological Research*, *96*(5), 343–349. https://www.sciencedirect.com/science/article/pii/S0953756209809489

Kalunke, R. M., Tundo, S., Benedetti, M., Cervone, F., De Lorenzo, G., & D'Ovidio, R. (2015). An update on polygalacturonase-inhibiting protein (PGIP), a leucine-rich repeat protein that protects crop plants against pathogens. Frontiers in Plant Science, 6, 146.

Koskiniemi, C., Truong, V. D., McFeeters, R., & Simunovic, J. (2012). Effects of Acid, Salt and Soaking Time on the Dielectric Properties of Acidified Vegetables. *International Journal of Food Properties - INT J FOOD PROP*, *16*(4). https://doi.org/10.1080/10942912.2011.567428

Liu, L., Wei, Y., Shi, F., Liu, C., Liu, X., & Ji, S. (2015). Intermittent warming improves postharvest quality of bell peppers and reduces chilling injury. *Postharvest Biology and Technology*, *101*, 18–25. https://doi.org/10.1016/j.postharvbio.2014.11.006

McFeeters, R. F., Bell, T. A., & Fleming, H. P. (1980). An endo-polygalacturonase in cucumber fruit. *J Food Biochem*, *4*(1), 1–16. https://fbns.ncsu.edu/USDAARS/Acrobatpubs/P121-150/p143.pdf

McMurtrie, E. K., & Johanningsmeier, S. D. (2018). Quality of Cucumbers Commercially Fermented in Calcium Chloride Brine without Sodium Salts. *Journal of Food Quality*, *2018*. https://doi.org/https://doi.org/10.1155/2018/8051435

Nielsen, S. S. (2019). *Food Analysis Laboratory Manual* (3rd ed.). Springer.

Ogasawara, S., Abe, K., & Nakajima, T. (2007). Pepper β-Galactosidase 1 (PBG1) Plays a Significant Role in Fruit Ripening in Bell Pepper (Capsicum annuum). *Bioscience, Biotechnology, and Biochemistry*, *71*(2), 309–322. https://doi.org/10.1271/bbb.60179

Ortiz, G. E., Guitart, M. E., Albertó, E., Fernández Lahore, H. M., & Blasco, M. (2014). Microplate assay for endo-polygalacturonase activity determination based on ruthenium red method. *Analytical Biochemistry*, *454*, 33–35. https://doi.org/10.1016/j.ab.2014.02.028

Péréz-Díaz, I., Breidt, F., Buescher, R. W., Arroyo-Lo´pez, F. N., Jime´nez-Dı´az, R., Ferna´ndez, A. G., Gallego, J. B., Yoon, S. S., & Johanningsmeier, S. D. (2013). *Fermented and*

Acidified Vegetables (F. P. Downes & K. Ito, Eds.; Fifth edition). APHA Press. https://ajph.aphapublications.org/doi/10.2105/MBEF.0222.056

Poverenov, E., Zaitsev, Y., Arnon, H., Granit, R., Alkalai-Tuvia, S., Perzelan, Y., Weinberg, T., & Fallik, E. (2014). Effects of a composite chitosan–gelatin edible coating on postharvest quality and storability of red bell peppers. *Postharvest Biology and Technology*, *96*, 106–109. https://doi.org/10.1016/j.postharvbio.2014.05.015

Prabha, T. N., Neelwarne, B., & Tharanathan, R. N. (1998). Carbohydrate changes in ripening Capsicum annuum in relation to textural degradation. *Zeitschrift Für Lebensmitteluntersuchung Und -Forschung A*, *206*(2), 121–125. https://doi.org/10.1007/s002170050226

Pressey, R. (1986). Extraction and assay of tomato polygalacturonases. *Undefined*. https://www.semanticscholar.org/paper/Extraction-and-assay-of-tomato-polygalacturonases-Pressey/d5df8a551c5fecddf5e6fa1d412c909249f6113c

Rao, T. V. R., Gol, N. B., & Shah, K. K. (2011). Effect of postharvest treatments and storage temperatures on the quality and shelf life of sweet pepper (Capsicum annum L.). *Scientia Horticulturae*, *132*, 18–26. https://doi.org/10.1016/j.scienta.2011.09.032

Sethu, P., Prabha, T. N., & Tharanathan, R. N. (1996). Post-harvest biochemical changes associated with the softening phenomenon in Capsicum annuum fruits. *Phytochemistry*, *42*(4), 961–966. https://doi.org/10.1016/0031-9422(96)00057-X

Torres, S., Sayago, J., Ordoñez, R., & Isla, M. (2011). A colorimetric method to quantify endo-polygalacturonase activity. *Enzyme and Microbial Technology*, *48*, 123–128. https://doi.org/10.1016/j.enzmictec.2010.04.004

Xin, Y., Liu, Z., Zhang, Y., Shi, X., Chen, F., & Liu, K. (2021). Effect of temperature fluctuation on colour change and softening of postharvest sweet cherry. *RSC Advances*, *11*(37), 22969–22982. https://doi.org/10.1039/D1RA02610K

Zhang, D., & Hamauzu, Y. (2003). *Phenolic compounds, ascorbic acid, carotenoids and antioxidant properties of green, red and yellow bell peppers*. https://scholar.google.com/scholar_lookup?title=Phenolic+compounds%2C+ascorbic+acid%2C+carotenoids+and+antioxidant+properties+of+green%2C+red+and+yellow+bell+peppers&author=Zhang%2C+Donglin+%28author%29&publication_year=2003

CONCLUSION

The key properties of acidified red bell peppers for microwave process design i.e., the electrical and thermal properties that influence its heating behavior when exposed to microwaves, have been characterized. The relevance of such properties in the context of process design has been explained in terms of heating uniformity influenced by depth of penetration and equipment design, and energy efficiency indicated by proportions of transmitted and reflected power. Such information provides fundamental insights to food engineers to optimize and propose a new process using microwaves for the development of clean label acidified red bell peppers, that are known to be the most susceptible to softening among other peppers. The continuous flow microwave processing of *salsa con queso* was experimentally shown earlier based on its uniform heating characteristics. The feasibility of such a multiphase product with a similar range of loss tangent to be processed using this technology, indicates the possibility of the same with acidified red bell peppers too. However, more information on the target enzyme that is responsible for softening and its thermal inactivation kinetics is required to direct further work in new process design.

Sensory quality is the most important driver for consumer satisfaction. While this work has laid down fundamental information for new process design, a tool for sensory quality evaluation has also been simultaneously developed. This will allow for including sensory quality testing as part of process optimization trials, paving the way for improved quality products and a relatively seamless scale-up of the new process. Thus, this work has initiated the development of clean label pickled vegetables using advanced processing technologies.